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倒立棒制御の仮想実験による人間の応答の統計的不変量の解明

Virtual Stick Balancing: Statistical Invariants of Human Response

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1. Introduction

There are many examples of human disappointing results and fails as well as mistakes while trying to prevent such undesired failures in operating facilities, machines, and vehicles. They are called human errors. In fact, as reported [1], in the last decade about 23% of all fatal accidents in worldwide commercial jet fleet were caused by controlled flight into terrain. Most of these errors are committed by people who are trying to do their job professionally and carefully. This fact suggests human errors must be considered as a normal component of human behavior. Hence, it is necessary to understand the nature of human control and human errors. Human control actions are usually divided into two levels: direct control behavior such as reflex movements as the lower order level and decision making as the higher order level, which needs complex knowledge and judgment. In this study, we focus on the direct control behavior. Now it is well established that the direct control exhibits three basic properties, intermittency, time-delay, and prediction. However, up to now human control is rather far from being understood well.

The present research is aimed at understanding the mechanisms of human control behavior based on virtual experiments using human-computer hybrid simulation. We study several simple examples of human-controlled systems, namely, the stick balancing control problem. Hybrid simulation is useful to record and analyze the behaviors of both human and controlled object.

In the previous research, the basic feature of human control behavior has been elucidated in case of the simple stick balancing control [2, 3]. To advance this line of research, we study the human control behavior through virtual experiment using three kinds of stick models [4]. These models are the simple stick, the triangle, and the vibrating stick. The triangle shape model disturbs human cognitive feature of stick angle. The vibrating stick model disturbs human cognitive feature of stick angler velocity. These models investigate what kinds of information humans focus on when they control the balance of a stick. It is necessary to make an experimental design preliminarily because we need a number of models and many subjects. For example, we must clarify the kinds of models, parameter values, number of subjects, experimental rules, the way of saving data, etc. We also collect a lot of data from the experiments. So, we need to analyze these data from various viewpoints such as the expectable universal behavior using phase trajectories and phase variables distribution, analysis of the skill, and the effect of human's learning and fatigue.

2. Method

2.1 Description of hybrid simulation

We consider the well-known control problem of stick balancing. In this thesis, we focus on simulating stick motion in viscous environment using a computer. The mechanical system under consideration is described by the following dimensionless mathematical model:

$$\tau\dot{\theta} = -\cos\theta + A \cdot v(t) \cdot \sin\theta. \qquad (1)$$

Here, θ is the angle of stick, τ is a time scale characterizing the operator perception, and the right-hand part of this equation represents the sum of friction and gravity force moments, $v(t)$ is the speed of cart motion which is actually the control parameter affected by system operator while A is the amplifying coefficient of control effort.

Based on this model, we developed the real time stick balancing simulator the example display of the simulator is shown in Fig.1. Here, we can change the parameters τ and A in the two lower-left textboxes. In the lower-right textbox, we can input experimenter's name which is used as data saving file name. We can also choose the performance or rehearsal by the lower-right listbox. The simulation starts when we click the start button. At that time, we can move the cart by moving the mouse from side to side in horizontal direction. Finally, the simulation finishes when we click the exit button. In the present experiments, three kinds of stick balancing simulation models were utilized. These models are the simple stick model (Fig.1), the triangle shape model (Fig.2) and the vibrating stick model (Fig.3). The reason why we use three kinds of models is to examine human cognitive features when he/she controls the stick. The triangle shape model disturbs human cognitive feature of stick angle. The vibrating stick model disturbs human cognitive feature of stick angular velocity.

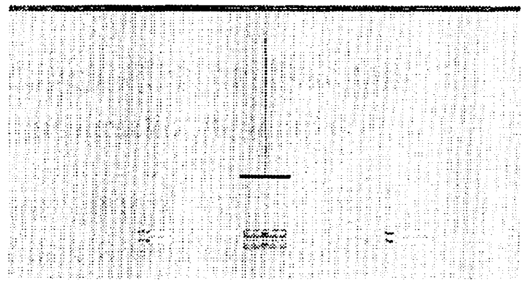


Figure 1: The simple stick model

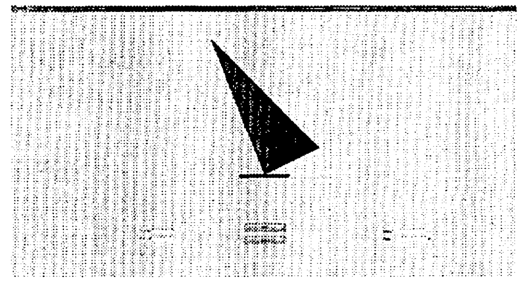


Figure 2: The triangle shape model

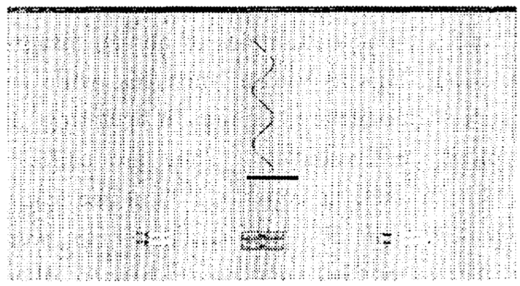


Figure 3: The vibrating stick model

2.2 Experimental design

In the experiments, we need to use a number of models and many subjects. Therefore, it is necessary to design experiments carefully to reduce their number. Here, we have to consider following issues:

(a) Parameters value setting in three kinds of models

(b) Selecting subjects for experiments

(c) Experimental rules

(d) Data storage

(a) Parameters value setting in three kinds of models

The model parameter τ is the control parameter of stick motion. Larger values of τ lead to slow stick motion and easy control. First, we made the trial experiments using $\tau = 0.7$. However, the results did not vary essentially from subject to subject because the control over the stick balancing was too easy. So, the parameter values used for later experiments were set to $\tau = 0.3$ and $\tau = 0.5$. The other parameter A was set to 0.7.

(b) Selecting subjects for experiment

The experiment results are expected to vary depending on personal skill of computer manipulation, age, gender, etc. So, different kinds of experiment subjects were desired to join the present experiment. However, it was difficult to gather many subjects. So, we selected the subjects based on the following criteria:

-Whether familiar with computers or not

-Whether familiar with present experiment or not

-Age

-Gender

We chose three participants who are familiar with the present experiment, three young students who are familiar with computers but not familiar with the present experiment, three senior female who are not familiar with computers and one senior male who are familiar with computers. Total 10 subjects were chosen.

(c) Experimental rules

We set a ten minutes session. Each examinee has to repeat the test when they fail within 10 minutes. From statistical analysis point of view, experimental data from a longer session are desired. But, examinee would feel tired if a session is too long. So, we set this moderately long period. We also set one minute rehearsal time. The reason why we prepare rehearsal time is to get beginners familiar with operation. Furthermore, when the stick control process continues after 10 minutes, we allow examinee to continue the experiment until 11 minutes.

We make the experiment with the order of stick balancing simulation models the simple stick model, the triangle shape model, and the vibrating stick model, since the simple stick model is the easiest task and useful for subjects to be familiar with this experiment. We also take a five minutes break between each experiment.

(d) Data storage

We saved time series data of time, angle of stick, angular velocity of stick, the position of mouse and speed of mouse at every 20msec, as the CSV form text file for later statistical analysis using MATLAB. The file name indicates the number of trials, date, hour and name of subjects. The data files are separately made for each trial. In addition, an integrated data file which include all trials data is also made for convenience of later analysis.

3. Result

Table 1 shows the list of subjects. Expert-A, B, C are familiar with the present experiment. Student-A, B, C and senior Male-A are familiar with computers but not familiar with the present experiment. The senior Female-A, B, C are familiar with neither computers nor the present experiment. By these wide ranges of subject types, we can analyze basic human control properties depending on age, the skill of computer manipulation, and the skill of the current experiment manipulation.

Table 2 shows the summary of the results from the experiments. Trial is the number of trials during 10 minutes test period. MaxTime is the maximum time of a single trial. The std(θ) and std(ω) mean standard deviation of angle and angular velocity of stick, respectively. As shown in Table 2, the subjects who are not familiar with the present experiment have lager number of trials and longer MaxTime. Moreover, they have lager std(θ) and std(ω). Furthermore, when the age is high and the task is difficult, the similar tendency is seen. Therefore, the four indexes in the Table 2 are proportional to the skill level of control.

Table 1: The list of subjects

	Age	Sex
Expert-A	22	Male
Expert-B	21	Male
Expert-C	27	Male
Student-A	24	Male
Student-B	22	Male
Student-C	22	Male
seniorFemale-A	56	Female
seniorFemale-B	58	Female
seniorFemale-C	61	Female
seniorMale-A	55	Male

Table 2: Results of the experiments

		Simple			
Name	τ	Trial	MaxTime	std(θ)	std(ω)
Expert-A	0.3	5	551.42	7.6	32.2
Expert-B	0.3	7	224.54	8.2	32.2
Expert-C	0.3	11	122.78	10.1	38.3
Student-A	0.3	47	61.66	17.4	66.6
Student-B	0.3	41	56.46	17.1	60.3
Student-C	0.3	45	121.42	18.1	82.3
seniorFemale-A	0.3	69	29.06	20.1	80.2
	0.5	31	98.86	12.4	38.9
seniorFemale-B	0.3	69	24.96	20.9	101.2
	0.5	16	174.66	11.0	48.4
seniorMale-A	0.5	13	139.24	12.6	62.7
seniorFemale-C	0.5	16	275.9	9.9	36.2
		Triangle			
Name	τ	Trial	MaxTime	std(θ)	std(ω)
Expert-A	0.3	38	68.34	17.8	90.0
Expert-B	0.3	19	124	15.3	65.4
Expert-C	0.3	48	25.06	23.5	91.3
Student-A	0.3	54	40.56	19.6	74.7
Student-B	0.3	96	39.8	24.1	84.7
Student-C	0.3	62	31.72	21.9	97.4
seniorFemale-A	0.3	124	11.26	26.4	90.3
	0.5	46	45.42	16.6	54.4
seniorFemale-B	0.3	91	20.14	23.7	98.9
	0.5	24	180.76	14.3	56.7
seniorMale-A	0.5	23	122.9	16.3	76.3
seniorFemale-C	0.5	30	148.16	14.2	43.7
		Vibration			
Name	τ	Trial	MaxTime	std(θ)	std(ω)
Expert-A	0.3	25	153.02	17.6	78.5
Expert-B	0.3	18	246.94	14.0	57.6
Expert-C	0.3	15	112.96	13.3	52.0
Student-A	0.3	97	28.64	26.0	101.0
Student-B	0.3	67	39.82	22.8	77.1
Student-C	0.3	58	40.32	22.3	95.0
seniorFemale-A	0.3	114	17.38	27.8	94.1
	0.5	63	23.46	23.6	66.9
seniorFemale-B	0.3	113	14.72	26.2	107.3
	0.5	29	139.56	17.5	57.5
seniorMale-A	0.5	29	99.12	17.9	66.4
seniorFemale-C	0.5	34	75.78	16.1	40.9

In the following figures, we show the detailed test results.

Figure 4 shows the phase trajectory of the simple stick model control. The phase trajectory is a trajectory of stick angle and angular velocity time series data. The left side of Fig. 5 shows the distributions of stick angle and angular velocity in linear scale whereas the right side shows the logarithm scale results. The distribution plots are commonly utilized to compare individual subject's control characteristics.

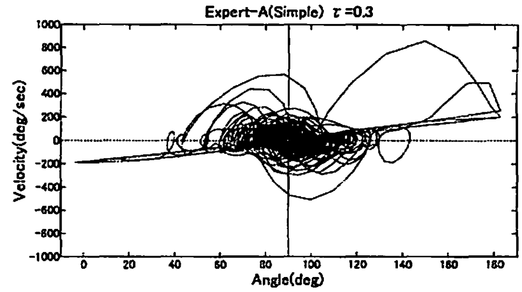


Fig. 4: The phase trajectory of the simple stick model

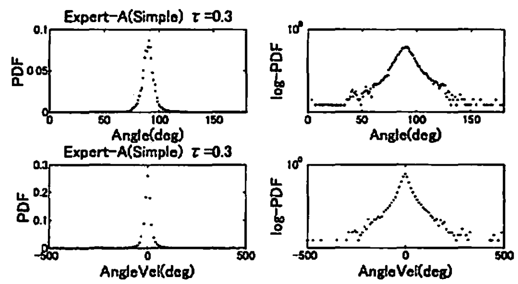
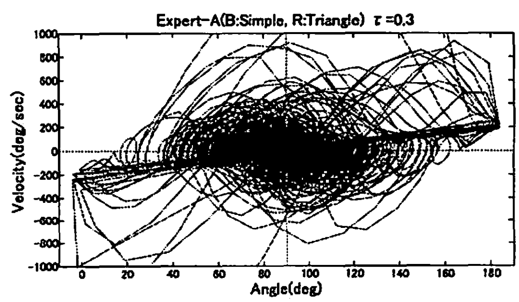
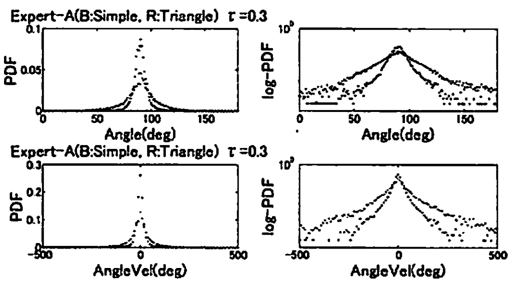


Fig. 5: The phase variables distributions of stick angle and angular velocity

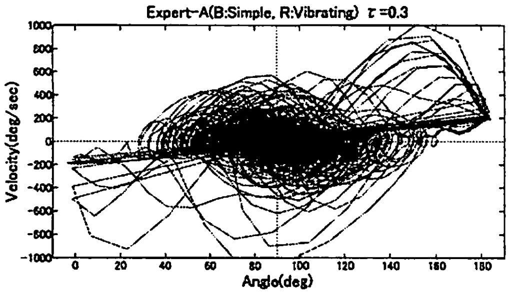
Figure 6 represents the phase trajectories and the phase variable distributions that compare the triangle shape model and the vibrating model with the simple stick model. In the triangle shape and vibrating stick models the fluctuation amplitudes are greater in comparison with the simple stick model. However, the function shapes seem to be the same (Fig. 6 (b) and (d)). It is also evident that the phase variables distributions of the triangle shape model and the vibrating stick model are similar (Fig. 6 (b) and (d)).



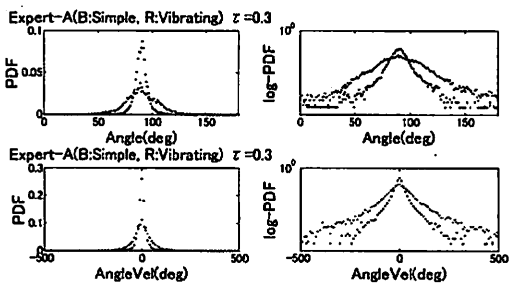
(a) The phase trajectory of the simple stick and the triangle shape models



(b) The phase variables distributions of the stick angle and angular velocity for simple stick and triangle shape models



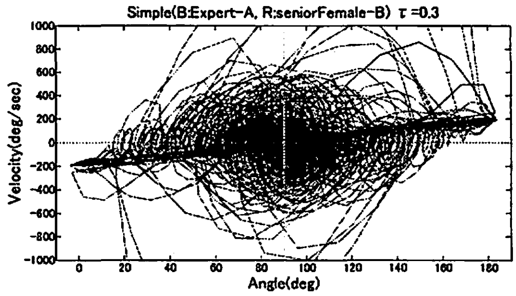
(c) The phase trajectory of the simple and the vibrating stick models



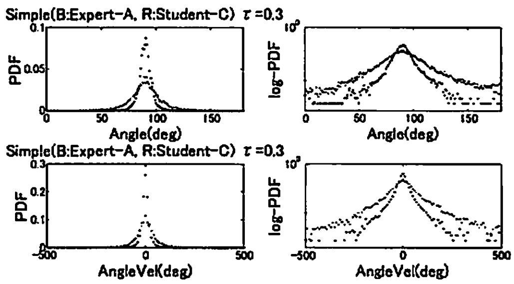
(d) The phase variables distributions of the stick angle and angular velocity for the simple stick and vibrating models

Fig. 6: Comparison among the models

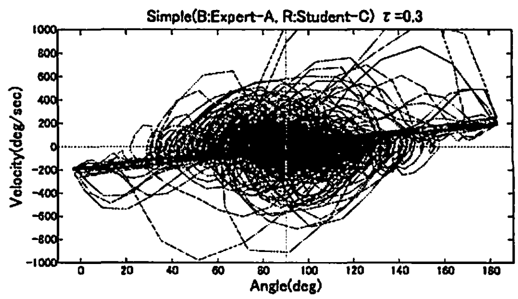
Figure 7 depicts the phase trajectories and the phase variables distributions that illustrates the differences between control behavior of subjects seniorFemale-B, Student-C and Expert-A. In case of seniorFemale-B and Student-C the amplitudes are greater in comparison with Expert-A. However, the function shape is the same (Fig. 7 (b) and (d)).



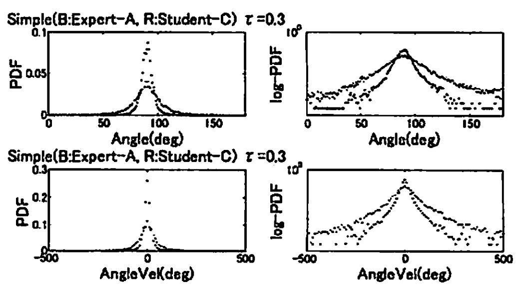
(a) The phase trajectory of Expert-A and seniorFemale-B



(b) The phase variables distributions of the stick angle and angular velocity



(c) The phase trajectory of the stick under control of Expert-A and Student-C



(d) The phase variables distributions of the stick angle and angular velocity

Fig. 7: Comparison among the subjects

Figure 8 shows the velocity time trend of the mouse during initial 5 seconds in one of the trials, for three typical subjects: Expert-A, seniorFemale-B and Student-C. The expert doesn't move so much, while the non-experts' control moves are wide and frequent. However, intermittent control feature was observed regardless of difference in age, skill, and difficulty of the model.

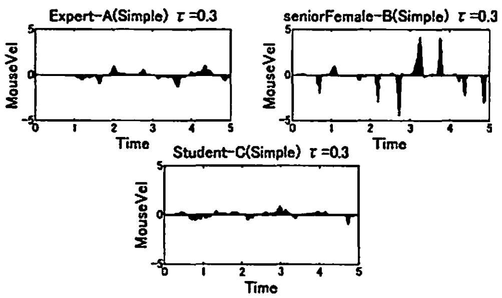


Fig. 8: Time trend of mouse verocity

Figure 9 illustrates detailed phase variables distribution structures around 90 degrees for three subjects. These results show the frequency is a little smaller at 90 degrees, which is the exact vertical position, than neighbor of 90 degrees. This fact shows all subjects start their control just after observing small deviations from the vertical position. This implies time-delay human control feature which is common to expert and non-expert subjects.

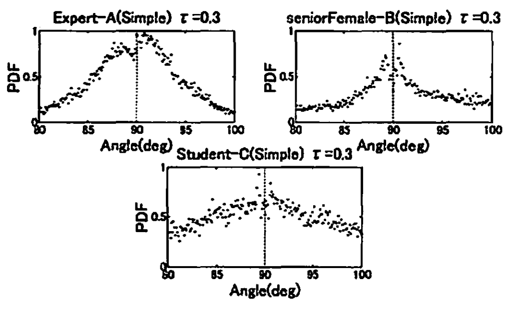


Fig. 9: Detailed structure of phase variable distribution

4. Conclusion

In the present days the fact that the human control of unstable systems is characterized by intermittence, time delay, and prediction is well established. However, the basic properties of human control are still rather far from being understood well. The present research has been aimed at finding some universal properties of human control by conducting virtual experiments on stick balancing.

We have considered three models of virtual objects whose dynamics is assumed to be overdamped, which mimics the balancing in viscous liquid. They are simple inverted pendulum, a triangle-shaped object and a vibrating spring. We hypothesize that in balancing the simple stick the operator reacts both to the stick angle and angular velocity, while in balancing the triangle and vibrating spring it is difficult to perceive the stick angle and the angular velocity, respectively.

We have found out that despite the difference in difficulty of the tasks, the statistical characteristics of human control are very similar for all the three kinds of the objects. The operator's age, skill, and the type of the model affect the amplitude of the object motion. However, three features of the operator behavior remains the same, they are (i) the general shape of both the angle and angular velocity distributions, (ii) the two-peaks structure of the angle probability density function, and (iii) the structure of the phase portraits formed by the object motion in the phase space angle - angular velocity.

The obtained experimental data also contribute to the evidence for the intermittency and time-delay in human control. The most important, though, is the universality of the distribution functions for all the participants and all the considered models. This fact could be possibly explained by the effects of learning how to balance a stick with minimal efforts. The evaluation of human's learning ability and the skill would be the possible future work.

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