ICAT '99

Force Feedback Device Control Utilizing Human Sensation Errors

Keitaro Naruse, Tohru Hayashi, Hideo Kita, Hiroshi Yokoi and Yukinori Kakazu

Complex Systems Engineering Laboratory,
Hokkaido University
Kita-13 Nishi-8, Kita-ku, Sapporo 060-8628 JAPAN
{naruse, tohru, kita, yokoi, kakazu}@complex.eng.hokudai.ac.jp

Abstract

A Force feedback or haptic device is one of the essential factors in a virtual reality system. However, a control task of the force display device is not an easy issue, because of large calculation time of positions and forces and oscillations between a human operator and the force feedback device. When we look at sensation characteristics of the human operator for perceiving the posture of his body, it is not so accurate. Then, a force feedback device control system can have a margin for the control accuracy so that we can improve the system bandwidth by utilizing the human sensation error. The objective of this paper is to discuss the human factors for position and force sensation, particularly for tolerance analysis of a human elbow joint and subjective force sensing by EMG signals.

In terms of the elbow joint analysis, we confirmed that the human operators can feel natural if their elbow joint angles are a little larger than the target angles, although each operator has his own acceptable range of variations. In addition, the smaller target angles permit more errors than the larger target angles. With respect to the EMG based force sensing system, we verified that the human operators have only a few levels for force magnitude sensing, and the EMG signals work well for human generated force sensing for the above levels of static loads.

Key words: Virtual reality, Force feedback device, Haptic device, Control scheme, Human sensation analysis

1. Introduction

The virtual reality is a new interfacing technology between a human operator and an artificial system, to which computers, sensors and mechanical devices are introduced for improving the operation quality of a human operator. One of the key issues to realize such a virtual reality system is a force display device, which is a mechanical device attached to the operator and gives a force or a torque to the operator in order to represent a mass, a friction force, and so on. However, a control task of the force display device is not an easy issue, particularly when the number of DOFs in the system becomes large. This is because it takes a large amount of time to calculate a set of forces applied to the human operator, which causes a less control bandwidth of the system and spoils the reality of the system.

However, if we look at sensation characteristics of the human operator for perceive the posture of his body, it is not so accurate. Then the force feedback device control system can have a margin for the control accuracy so that we can improve the system bandwidth by utilizing the human sensation error.

The objective of this paper is to discuss the human factors for position and force sensation. In terms of the position errors, we make the analysis of angle resolution of the human operator. We focus on an elbow joint for the analysis to see how much the operator permit an error between an actual elbow angle and an angle the operator feel at, with the conditions of a) the effect of visual information and b) the one of a given specific target angle. The analysis result shows that the human operators can control their own elbow more precisely when the above information of visual and angle than no information. The human operators can feel natural if their elbow joint angles are a little larger than the target angles, although each operator has his own acceptable range of variations. In addition, the smaller target angles permit more errors than the larger target angles.

On the other hand, for the force sensing, we focus on an EMG (electromiogram) signal. Since the EMG signal is a composite signal of muscle actuation vital ones measured on a skin surface, the EMG signal includes information which, how many and how much muscles are activated. In addition, since the operator generate a force by reacting with an artificial load in the virtual reality system, the EMG signal can reflect potentially how heavy the operator feel the artificial load. The objective is to develop an EMG based force sensor system with the learning of EMG signal variations of each operator. Experimental results of the proposed system show that it can be a complementary force sensing one to a conventional one such as a physical force sensor in a virtual reality system.

2. Force Display Control Problem

In this section, the problems of force display control are discussed. First, representative research projects about the development of force feedback devices are shown briefly. Then, the research issues in the force display control are discussed. Considering the research issues, two substantial approaches to solve the issues are discussed from the both viewpoints of mechanical properties and the sensation of an operator.

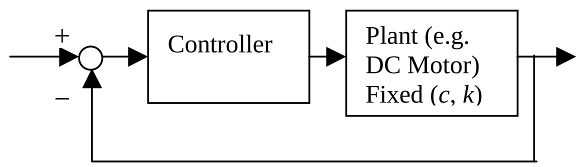
Yoshikawa proposed several types of force display devices with a link structure as an external machine, and proposed a force control scheme for the devices considering a force in the system by force sensors attached to the force display system. Iwata proposed several kinds of the force display device. One is three-dimensional joystick called Haptic Master and the other is the combination of a screen and force display device called Haptic Screen. Tachi proposed two and half dimensional force display system called PANDRA with the impedance control. Sato developed a wire-driven force display device for a total body placed in a specialized room called SPIDER. Hirose proposed the hardware design of wearable force display device for an arm. PHANToM by SensAble Technologies, one of the most famous commercial platform of the force display device, and it can represent a point in the three dimensional space.

There are the following two major difficulties on controlling the force feedback device. The first one is called the man-in-the-loop problem, whihch is illustrated in Fig. 1. It means that there exists a human operator, who can change his mechanical impedance by straining his muscles, in a control loop, which can be the control system unstable. Therefore, the control system should cope with the changes. The other difficulty is a bandwidth of the control system. It has bee pointed out that the control system of the force feedback device should run faster than 1000 Hz. Therefore, if there is a number of objects in a virtual world, positions and forces calculation becomes large and it can cause smaller bandwidth. Even the bandwidth is fast enough, if an output from actuators or feedback gains of the force feedback device are small, the response of the device becomes poorer, and it spoils the reality of the system as well.

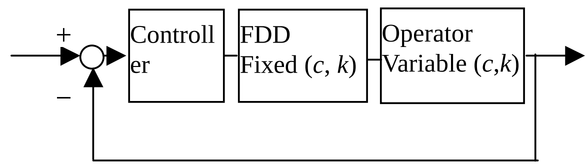
On the other hand, the objective of the virtual reality system is to let a human operator feel natural as he is in the real world. It means that we do not have to go through a large amount of the calculation to determine the positions and forces of the virtual objects. Instead, it is enough to put rough estimated positions and forces to the human operator in the range that he cannot perceive the differences of the estimated and exact ones. This is the motivation of this paper, and we call the solution as human based approach.

In order to achieve the human based approach, we should consider the modeling and sensor system. The modeling is to investigate how much the human operator allows an error between the exact and estimated positions and forces. Then we utilize the analysis result to realize fast position and force calculation. The other issue is how to develop a sensor system, which can measure subjective human perception such as heave and light. In this paper, for the first issue, we analyze an error sensation of an elbow joint and model them. For the last issue, we try to develop a sensation based force sensor system based on EMG signals.

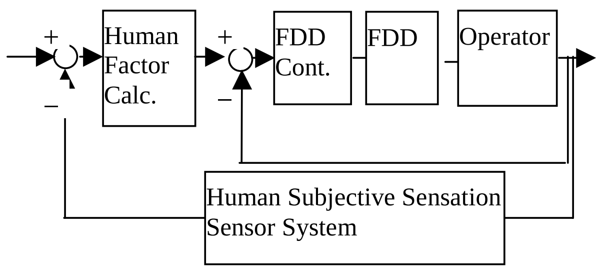
However, the sensation of the position and force changes by the following three factors. i) Fatigue: when an operator is tired or gets exhausted, he feels heavier force for a specific force than usual. ii) History of operations: if the operator did heavy loads just before a current task, he feels lighter force for the specific force than usual. These two happens within the operator. iii) Individual constitution: if the operator has more developed muscles than the regular persons do, he feels lighter force for the specific force than they do. Therefore, the system should involve a learning mechanism to deal with the variations.



(a) A conventional mechanical system.



(b) A force display system.



(c) The proposed human based force display system.

Fig. 1: Control loop structure.

3. Analysis of human elbow joint resolution

In this section, we analyze the difference between an actual angle and perceived angle of an elbow. Subjects are four males of 22 to 26 years old. They put an angle measurement device on their elbow, and to see the effect of visual and target angle information as well as the basic properties. The experimental procedure is as follows: i) one of the seven target angles of 0, 15, 30, 45, 60, 75 and 90 degree is applied to each subject in each trial. In each trial, a target angle is selected among the seven angles randomly. The process continues 50 times trial for each each target angle. ii) The two information of visual (watching their own arm directly) and target angle (display them the target angle by bending their arm to the angle) are applied to them. iii) After bending their arm, they straighten their arm for getting rid of the context effect of previous angle. Fig. 2 shows the apparatus of experiment.

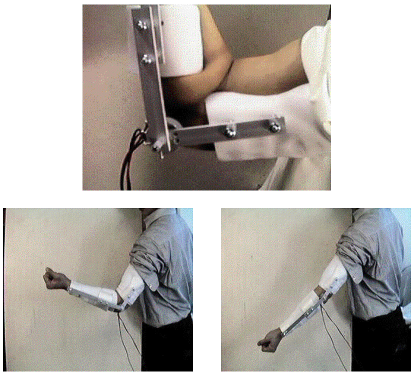


Fig. 2: An elbow joint angle experiment apparatus.

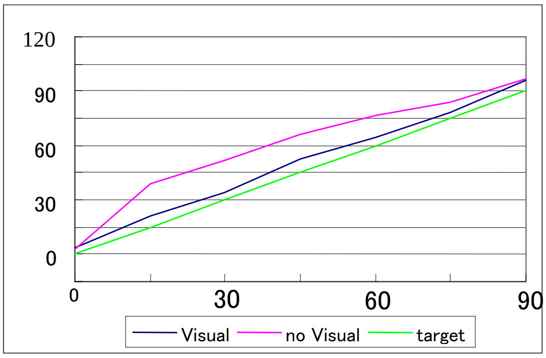


Fig.3: Average of all subjects on actual joint and target angles.

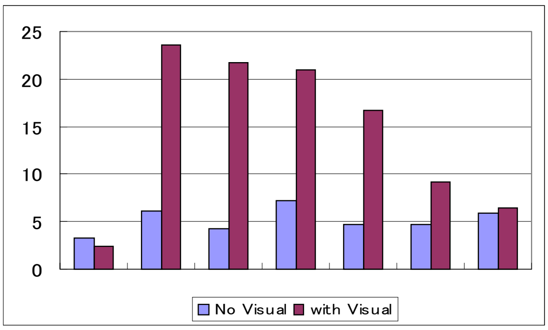


Fig. 4: Errors on Fig. 3.

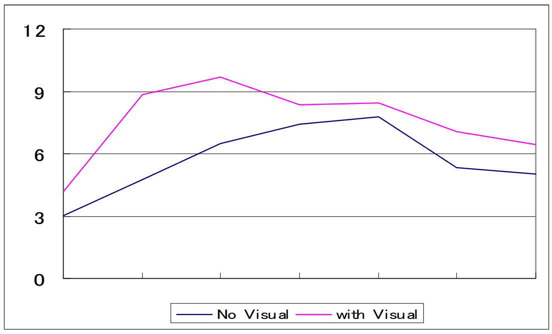


Fig. 5: Standard deviation on Fig. 3.

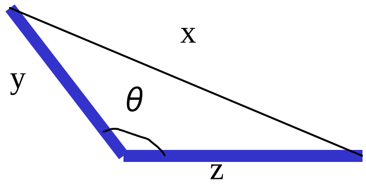


Fig. 6: Simple elbow tendon model.

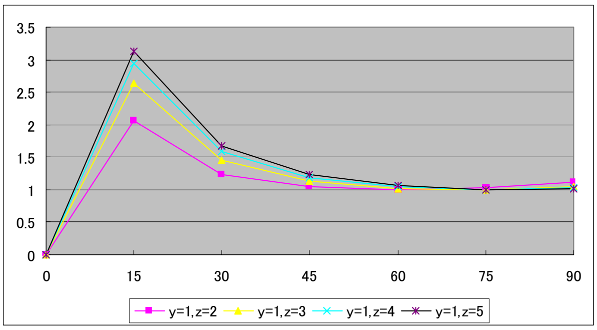


Fig. 7: Simulated errors based on the model.

Fig. 3 shows the average of actual angles for each target angle with and without visual information. Fig. 4 and Fig. 5 show the errors and the standard deviations on Fig. 3. From these figures, we confirm the followings. i) The actual angle is always larger than the target angle. Ii) The visual information helps the subjects so much to reduce the errors. iii) At 0 and 90 degree, the errors between the actual and target angles are smaller than the others. This is due to the mechanical limitation of the elbow joint. iv) The smaller target angles have larger errors. v) The repeatability of the angle does not depend on the magnitude of the target angle.

In order to model these phenomena, we make a simple model on the elbow errors. Suppose the elbow joint is rotated by a tendon, and the accuracy of pulling the tendon is assumed to be a fixed value. Then the angle error can be modeled as in Fig.6 and expressed as

$$d\theta = \frac{y^2 + z^2 - 2xy\cos\theta}{xy\sin\theta}dx\,, \qquad (1)$$

where dx and $d\theta$ are a small displacement on x and θ, respectively. Fig. 7 shows the relation between x and q with various *y* and *z* values, and the figure fits well to actual result. We can estimate the elbow angle errors by the equation.

4. Development of Force Sensing System with EMG signals

We introduce an EMG signal as a basic sensory input, because the EMG signals are a sequence of vital voltage changes when muscles are strained, measured on a surface of a skin. It has been known that the EMG signals show a specific frequency for each muscle, and the amplitude of the signals is related to the amount of a force. Therefore, in this section, we analyze the relationship between the EMG signals and the status of the muscles of the operator, in other words, the relations to the force and posture of the operator.

Fig. 8 illustrates the flow of signals to a force sequence generated by straining muscles and EMG signals when an objective is given. The development of the force sensing system is to generate a mapping from the EMG signals to the force sequence. Suppose F_1 and F_2 are two of force vectors, and E_1 and E_2 are corresponding EMG signal vectors, for discussing the realizability of the EMG signals as the force sensing system, the following factors should be analyzed. i) If F_1 and F_2 are recorded from the same operator at the same time for the same task with the same load, the differences between E_1 and E_2 correspond to the *repeatability*. ii) If F_1 and F_2 are recorded from the same operator at the same time for the same task but *different loads*, the differences between E_1 and E_2 correspond to the *scalability*. iii) If F_1 and F_2 are recorded from the same operator at *different times* for the same task with the same load, the differences between E_1 and E_2 correspond to the *variation in an operator* such as *fatigue*. iv) If F_1 and F_2 are recorded from *different operators* at the same time for the same task, the differences between E_1 and E_2 correspond to the *variation among operators*.

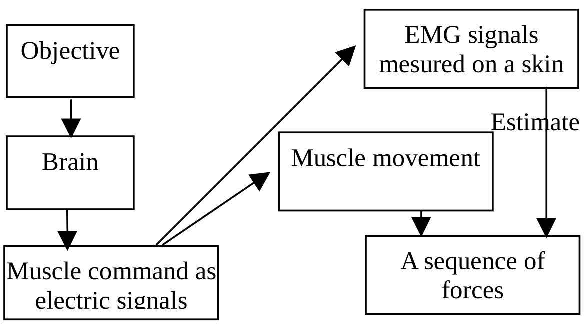


Fig. 8: Flow of signals for straining muscles and the estimation of force sequences by EMG signals.

For analyzing these four factors, preliminary experiments are carried out for a static task, which means a task given to the operator is to hold a load in a same posture. This is set up to analyze basic relations between the force and EMG signals. The analysis for dynamic task, which is to move the operator body in a specific sequence, is one of the future works.

The EMG signals are measured by Delsys EMG electrodes with 12-bit discritization in the sampling rate of 800Hz. The objective is to investigate the EMG signals for the task of holding a load of 0 kg, 1 kg, 2.5 kg and 5 kg for the palm up and down with keeping the elbow joint straight. Four EMG electrodes are used and placed as shown in Fig. 9, which are considered as typical muscles to rotate the elbow joint. The EMG signals are preprocessed with the integration of the absolute of the sensor value for seeing the amplitude of the EMG signals and the Fast Fourier Transform (FFT) to see the frequency spectrum.

In order to estimate the load, we made the analysis on the amplitude of the signals by the integral of the square of signals. Fig. 10 shows the average of the integral of the EMG signals for, (a) the operator A with the palm up, (b) the operator A with the palm down, and (c) the operator B with the palm up. From the figure 5(a) and (b), we confirmed that the discrimination of the two static postures is possible because the two patterns indicate totally different ones. In terms of the scalability, we see the monotone increase of the integral values as the load goes larger. However, we can see the much variation among the operators from (a) and (c). Although the effect of the fatigue is not shown in these figures, we found the data of increasing the integral value in the period of 30 seconds to 60 seconds particularly as a load is heavy. Furthermore, during the period, the pattern of the integral of the four signals was changed into another one, because the operator changed the balance of his muscles unconsciously by moving his arm slightly in order to which shows the to endure the load. In addition, when making the data acquisition in another day, the sensing conditions of the electrodes location, the contact pressure of the electrodes and the skin surface are different even though they are carefully set up, which causes the less repeatability on the EMG signals.

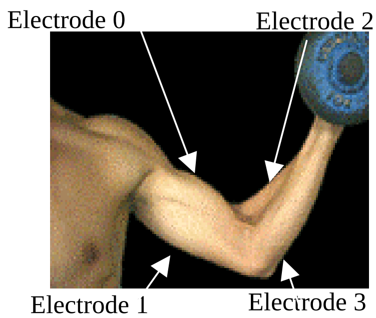


Fig. 9: Location of the four electrodes

From these results of the preliminary experiments, we confirmed that the load and posture are possible to discriminate when EMG signals are taken from a single operator without taking off the electrodes, which is due to the repeatability of EMG electrodes set-up. In this case, the relation between the EMG signals and the load and the posture can be learned by a layered neural network. However, if one of the factors is changed, it is not guaranteed that the network estimates the loads and the posture correctly. Therefore, we introduce a concept of the profile, which is a group of data set of signals possible to discriminate by a same network.

First, we trained a layered network for a single data set to see the basic learnability of the network and the generalizability for another data sets. The conditions of the EMG signals acquisition are same as the one in the previous section. We prepared the four different sets of training data in the experiments: (a) the operator A in one day, (b) the operator B in another day, (c) the operator A in the other day, and (d) the operator B in one day, for the same electrode locations and the same task. Therefore we employed four networks, and each network has four input units which corresponds to the four channels of the EMG signals, sixteen hidden units and five output units which are one for a posture (palm up or down) and the four degree of loads (0, 1, 2.5, 5 Kg). Each network is trained with a specific teacher set of twenty four records until the error becomes small enough by the error backpropagation algorithm, then the network is tested by the four test set of eight records which are not included in the teacher set. Table 1 shows the result of the discrimination. From this, we can see that each network can learn a single data set very well, however each of them cannot work well for the other three test sets.

In order to see how many the neural networks are needed to estimate the force, we made the following experiment. When a new data set is inputted to the system, if the set is similar to the already trained patterns, the system merge it to the network. Otherwise, the system creates a new network for the new pattern. Table 2 shows the results. The system creates three categories out of the four data sets, merging the data sets of (b) and (c) into one. Looking the raw data of the four data sets for the analysis, the data sets (b) and (c) have almost same distribution of values, while the data set (a) has larger values than the data sets of (b) and (c), which can be due to the position of the electrodes and the conditions of the skin surface, and the data set of (d) is pretty different because the data set is taken from the other operator.

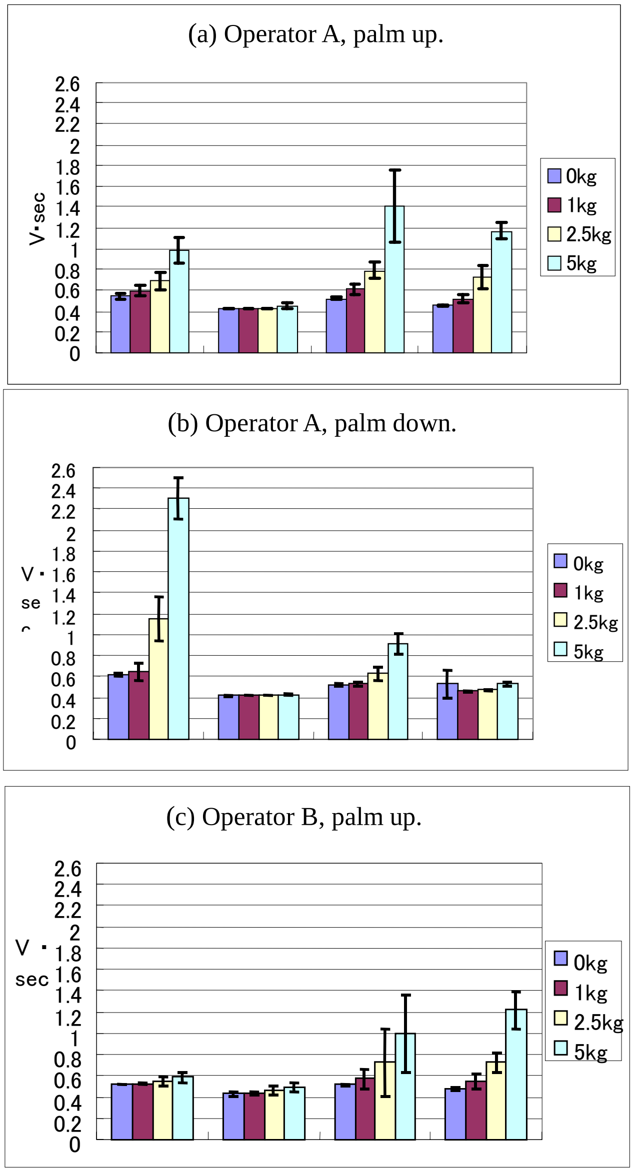


Figure 10: Average of the integral of the EMG signals.

Table 1:Discrimination results of the four training sets and the four test sets by the four single artificial neural networks. (a) Operator A in one day; (b) Operator A in another day; (c) Operator A in the other day; (d) Operator B in same day as (a).

	Training set (a)	Training set (b)	Training set (c)	Training set (d)
Test set (a)	**7/8**	4/8	5/8	3/8
Test set (b)	3/8	**8/8**	2/8	3/8
Test set (c)	5/8	4/8	**8/8**	3/8
Test set (d)	2/8	1/8	2/8	**7/8**

Table 2: Created profiles (artificial neural networks) with the same data sets as Table 1.

	ANN 1 incl. (a)	ANN 2 incl. (b) (c)	ANN 3 Incl. (d)
Test set (a)	**8/8**	1/8	1/8
Test set (b)	2/8	**8/8**	2/8
Test set (c)	2/8	**8/8**	1/8
Test set (d)	1/8	3/8	**8/8**

5. Conclusions

For the objective of the development of the EMG based force sensing system, we did the followings in this paper. i) The problem of controlling the force display device was discussed from the two viewpoints of the mechanical system and the sense of an operator. Then, the necessity of the adaptable force display control system was discussed. ii) The error sensation on the elbow joint is analyzed and modeled. iii) The basic properties of the EMG signals are examined and discussed. iv) The EMG based force sensor system, which is capable of coping with the variations of the signals, is developed by introducing the artificial neural networks as the profile. v) The experimental results show that the proposed system can estimate the load and static posture by the EMG signals in the different operators and in the different situation.

Of course, the proposed EMG based force sensor system is not accurate as the conventional force sensors such as a physical force sensor. Rather the proposed system is a complementary one to the conventional ones, and it has the advantage of estimating an internal state of an operator such as muscle straining, as well as the advantage of a human evaluation system which is to see if the operator feels the virtual world as same as in the real world.

References

1. G. Burdea and P. Coiffet, “Virtual Reality Technology,” New York: Wiley, (1994).
2. G. C. Burdea, “Force and Touch Feedback for Virtual Reality Technology,” New York: Wiley, (1996).
3. T.Yoshikawa, Y.Yokokohji, T.Matsumoto, X.-Z. Zheng, “Display of Feel for the Manipulation of Dynamic Virtual Objects,” Trans. of ASME J. of DSMC, vol.117, no.4, pp.554-558, (1995).
4. T.Yoshikawa and H.Ueda, “Construction of Virtual World Using Dynamic Modules and Interaction Modules,” Proc. of 1996 IEEE Int. Conf. on Robotics and Automation, (1996).
5. H. Iwata, “Haptic Screen,” Proc. of Japan Society of Virtual Reality (in Japanese), vol.1, pp. 7-10, (1996).
6. K. Arai, T. Maeda and A. Tachi, “Haptic Display: PANDRA the first report (in Japanese),” Proc. of 12th Human Interface Symposium, pp. 287-290, (1997).
7. S.Tachi: “R&D Projects on Virtual Reality and/or Tele-existence,” The 4th Industrial Virtual Reality Show & Conference (IVR'96), pp.6-11, (1996).
8. H. Kushida, M. Ishii and M. Sato, “Multimordal Fullbody Virtual Environment Big SPIDAR,” Proc. of 2nd Japan Virtual Reality Conference, pp. 131-132, (1997).