A Data Adjustment Method of Low-priced Data-glove Corresponding with each User Hand

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***Abstract*—A data glove is one of the major interfaces which are used in the field of virtual reality. An expensive data glove with a lot of sensors can get detailed data about finger joint angles. However it is too expensive to use in ordinary home. There is a low-priced data glove, but it does not have enough sensors to get detailed data. We have proposed the method to obtain all finger joint angles from low-priced data glove by estimating the types of hand motions from sensor values. In this method, we assume some representative hand motions and consider that other hand motions can be represented as synthetic motion of them. However parameters to calculate angles are gotten from pre-experiment for specific user, and they are not appropriate for other users. In this paper, we suggest the method to determine parameters for each user hand automatically.**

I. INTRODUCTION

Virtual Reality (VR) is the rapidly growing research field in recently years. VR technologies give us various merits. There are simulators to practice an operation and fly a plane as examples of VR technologies[1]. These simulators can enable us to avoid the risk and save the cost. A data glove is one of the major interfaces which are used in the field of VR. Until today, various types of researches about data glove have been conducted[2][3][4]. Data gloves measure curvatures of fingers using bend sensor. A data glove with a lot of sensors can get detailed data about finger joint angles, and it enables to obtain finger joint angles accurately. However, this data glove is too expensive to use in ordinary home. There is a low-priced data glove but it can not get detailed data because it does not have enough sensors. For example, the 5DT Data Glove 5 Ultra and Essential Realty P5 Data Glove have a single sensor on each finger, so they have five sensors in the whole hand (Fig. 1, 2, 3). However there are three finger joints for each finger, a single sensor can not measure all of these three angles directly. In our laboratory, we have proposed a data adjustment method of low-priced data gloves[5]. This method enables to obtain all finger joint angles by estimating the types of hand motions from a low-priced data glove. We assume some representative hand motions, and consider that other hand motions can be represented as synthetic motion of them. The pilot system was specified for specific user, and it could not be applied for any users. Even if another user moves his/her hand same as the specific user, the sensor values obtained from data glove are different from the specific user's one. It means that the pilot system can not estimate any user's angles exactly, and we need to give calibrated parameters

Fig. 1. 5 DT Data Glove 5 Ultra

Fig. 2. P5 Data Glove

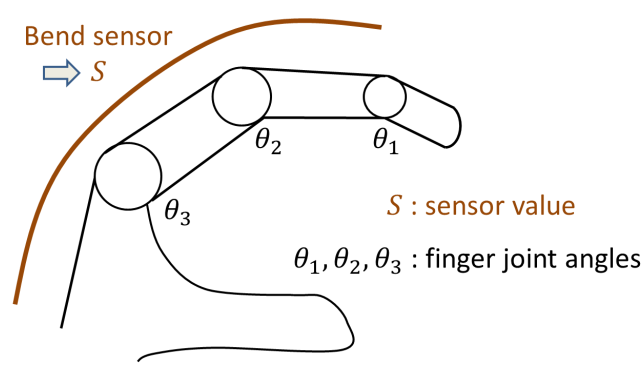

Fig. 3. Finger and bend sensor

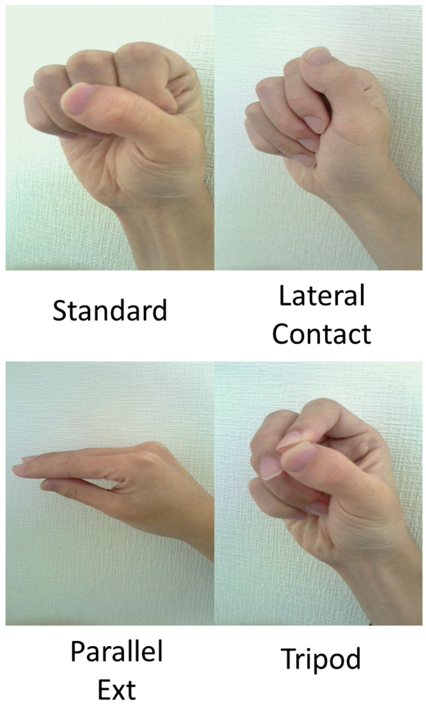

Fig. 4. Representative hand motions

for estimation equations to each user. The parameters have to be given through pre-experiment for each user, and it has much trouble. In order to solve this problem, we focus on the size of hand[6]. We assume that the differences of the sensor values are caused mainly by hand size. We investigated the correspondence of hand size to difference of the sensor values in advance. Also we propose a method to determine parameters from only user's hand size.

II. ESTIMATION OF FINGER JOINT ANGLES

In this section, we describe a estimation method of finger joint angles which have been proposed in our laboratory until now.

A. Representative Hand Motions

To estimate finger joint angles, this method limits user's hand motion to grasping motion. First of all, we choose several representative hand motions from human's grasping motion (Fig. 4)[7][8].

Furthermore, we assume that human's grasping motion can be represented as synthetic motion of them. To derive three finger joint angles from a single sensor value, we use the following method. We get the sensor values with the low-priced data glove when doing each grasping motion. Also, we get true angles of finger joints at that time. Provided that we use true angles obtained from a data glove which has a lot of sensors. We use Immersion CyberTouch as data glove with a lot of sensors. Then, the sensor values and the true angles of finger joints at the same time are associated. We show an example of correspondence in Fig. 5.

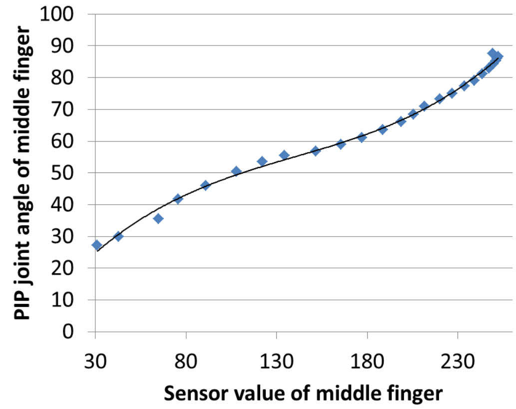

Fig. 5. Example of correspondence

We derive the following numerical formulas using these correspondence.

$$\theta_{pi1} = \frac{2}{3}\theta_{pi2} \tag{1}$$
$$\theta_{pi2} = E_{pi2}S_i^3 + F_{pi2}S_i^2 + G_{pi2}S_i + H_{pi2} \tag{2}$$
$$\theta_{pi3} = E_{pi3}S_i^3 + F_{pi3}S_i^2 + G_{pi3}S_i + H_{pi3} \tag{3}$$

Where motion p is one of representative hand motions. Angles θ_{pi1}, θ_{pi2} and θ_{pi3} express the DIP, PIP, and MP joint angle of the finger i for the motion p. The DIP, PIP, and MP joint mean the first, second and third joint of a finger respectively. The S_i is sensor value of finger i. And E_{pij}, F_{pij}, G_{pij} and H_{pij} are constant parameters for the motion p, finger i and joint j. These parameters, E_{pij} to H_{pij}, are calculated by pre-experiment. Besides, DIP joint angle is obtained by proportional connection with PIP joint angle (eq. 1)[9]. Joint angles of finger i of motion p are obtained by these numerical formulas.

B. Hand Motion Estimation and Angles Estimation

To represent user's hand motion as synthetic motion of representative hand motions, we need to know how similar user's hand motion to which representative hand motions[10]. Then, we set the following formula based on the probability density function of the multivariate normal distribution for n points in the five dimensional feature amount space.

$$L_{pn} = exp\{-\frac{1}{2}(\boldsymbol{S} - \boldsymbol{\mu}_{pn})^T \boldsymbol{\Sigma}_{pn}^{-1}(\boldsymbol{S} - \boldsymbol{\mu}_{pn})\} \tag{4}$$

Where $\boldsymbol{S}$ is the sensor value vectors. And $\boldsymbol{\mu}_{pn}$ and $\boldsymbol{\Sigma}_{pn}$ represent mean vector of sensor sample values, variance-covariance matrix of point n (an integer satisfying $1 \leq n \leq 25$) in representative hand motion p. Besides, $\boldsymbol{\mu}_{pn}$ and $\boldsymbol{\Sigma}_{pn}$ are obtained by pre-experiment for specific user. If the sensor values are obtained actually from the glove, we select the maximum value according to the following formula.

$$L_p = \max_n\{L_{pn}(\boldsymbol{S} : \boldsymbol{\mu}_{pn}, \boldsymbol{\Sigma}_{pn})\} \tag{5}$$

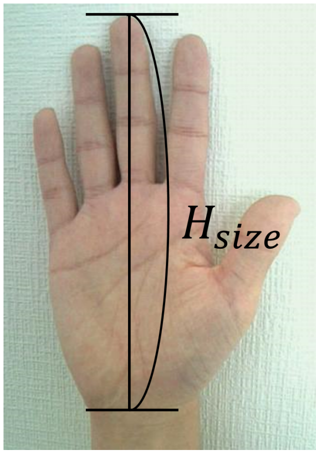

Fig. 6. Definition of hand size

TABLE I
H_{size} OF EACH PARTICIPANT $[cm]$

	H_{size}	standard deviation
participant 1	17.0	-
participant 2	18.1	-
participant 3	20.5	-
sample person	17.7	-
average of Japanese male[11]	18.3	0.8
average of Japanese female[11]	16.9	0.7

TABLE II
JOINT ANGLE ERROR OF GRASPING PLASTIC BOTTLE [DEGREE]

	Thumb	Index	Middle	Ring	Little	avg.
sample	7.6	17.9	11.2	16.2	14.8	13.6
participant 1	31.1	17.7	26.4	5.0	5.1	17.1
participant 2	15.3	17.7	11.6	11.7	5.0	12.3
participant 3	30.2	10.5	27.2	17.7	17.7	20.7

Thus, we get the likelihood on representative hand motion p in current sensor values. After that, we decide the ratio r_p of hand motion p according to the following formula.

$$r_p = \frac{L_p}{\Sigma_{p=1}^{P} L_p} \tag{6}$$

Where P is the total number of representative hand motions. As stated above, we can obtain θ_{pij} and r_p. At last, θ_{ij} is derived by following formula.

$$\theta_{ij} = \sum_{p=1}^{P} r_p \cdot \theta_{pij} \tag{7}$$

III. DIFFERENCE OF HAND SHAPE

In the method stated in previous section, parameters are needed to be precomposed for each user. However, using an expensive glove to obtain the true angles of finger joints is not suitable from perspective of utilization in ordinary home. Furthermore, parameters to calculate angles are obtained by a lot of trials of hand motions. They are troublesome for general user. In this section, we try to determine the parameters automatically for motion and angles estimation.

A. Estimation Accuracy between Different Users

We investigated estimation accuracy between different users. With the cooperation of three research participants, we had an experiment. In this experiment we asked each participant to grasp a plastic bottle ($500ml$) with equipped data glove. The reason to choose this grasping motion was user's hand motion is little by little different every time even if user thinks that he/she performs the same hand motion. And we defined the hand size of user as H_{size}, which is decided by the distance from the wrist to the top of the middle finger (Fig. 6). The H_{size} of each participant is shown in Table I. The sample person is who provided each parameter for estimation in pre-experiment. And the parameters for estimation were obtained by the sample person's hand. When each participant grasped the plastic bottle, their finger joint angles were estimated by these parameters of sample person. We measured finger joint angles when their hand was touching completely with the plastic bottle. And we investigated the average of the errors between estimated finger joint angles and obtained angles by CyberTouch. Table II shows the results. These results indicate that estimation accuracy using parameters of the person whose hand size is different becomes worse. We expected that joint angle errors of the sample person was minimum because sample person's parameters were used for estimation. However the average error of participant 2 was minimum in Table II. We concluded that the reason was the sensor values were not uniform but also scattering when user moved one's hand. However, only because of these numerical values, the results can not be judged whether they are significant or not. Then we had statistical hypothesis testing to confirm these results are significant. At this time, we adopted Student's t-test. We had Student's t-test to the average of joint angle errors of the sample person and other participants. Test statistic t_0 is obtained from the following formula.

$$t_0 = \frac{|\bar{X} - \bar{Y}|}{\sqrt{U_e(\frac{1}{m} + \frac{1}{n})}} \tag{8}$$

Where $\bar{X}$ and $\bar{Y}$ are the average of joint angle errors, m and n represent the sample size of two groups. And U_e is obtained from the following formula.

$$U_e = \frac{(m-1)U_x + (n-1)U_y}{m+n-2} \tag{9}$$

Where U_x and U_y are unbiased variance. As stated above, test statistic t_0 can be obtained and t_0 follows t distribution. P-values obtained from Student's t-test are shown in Table III. The $P(T \leq t)$ represent significance probability. In this paper, we decide that significance level α is 0.05. So it is statistical significance if $P(T \leq t)$ is smaller than 0.05. Looking at Table III, the $P(T \leq t)$ in all categories are smaller than 0.05. They indicate that there are statistical significance in estimation accuracy between the sample person and other participants. We confirmed necessity of determining parameters for each user.

TABLE III
P-VALUES OF STUDENT'S T-TEST

	$P(T \leq t)$
participant 1	6.8×10^{-6}
participant 2	1.0×10^{-2}
participant 3	9.6×10^{-4}

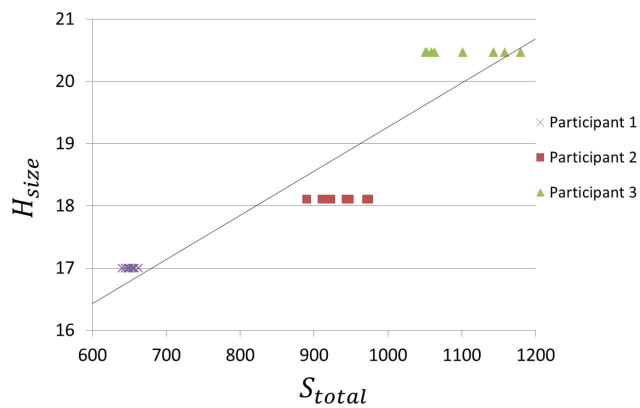

Fig. 7. Relation between H_{size} and S_{total}

B. Hand Size Estimation

We assume that parameters to calculate finger joint angles are determined by knowledge of user's H_{size}. To evaluate user's H_{size}, we try to use the sensor values when user performs one hand motion. When deciding hand motion for estimation of hand size, it is important that a hand motion is simple. If it is obscurity motion, there is difficulty in performing hand motion. Then, we consider the total value of five sensors when user closes hand (=S_{total}). We obtained S_{total} and each H_{size} from each research participant. The correspondence between H_{size} and S_{total} is shown in Fig. 7. Then we conclude the following formula.

$$H_{size} = aS_{total} + b \tag{10}$$

Where a, b are constant parameters. Using this formula, user's H_{size} can be obtained by performing the simple hand motion.

C. Determination of Estimation Parameters

We would like to determine the estimation parameters of new user whose H_{size} is h_u. The size h_u is obtained by eq. 10. If two of the three participants are A and B, each hand size is h_A and h_B respectively ($h_A > h_B$), the parameters for h_u user are defined as below.

$$E_{upij} = \frac{(h_u - h_B)E_{Apij} + (h_A - h_u)E_{Bpij}}{h_A - h_B} \tag{11}$$

$$F_{upij} = \frac{(h_u - h_B)F_{Apij} + (h_A - h_u)F_{Bpij}}{h_A - h_B} \tag{12}$$

$$G_{upij} = \frac{(h_u - h_B)G_{Apij} + (h_A - h_u)G_{Bpij}}{h_A - h_B} \tag{13}$$

$$H_{upij} = \frac{(h_u - h_B)H_{Apij} + (h_A - h_u)H_{Bpij}}{h_A - h_B} \tag{14}$$

TABLE IV
EXAMPLE OF SENSOR VALUE FOR MOTION p AT THE TIME t

trial	Thumb	Index	Middle	Ring	Little
1	s_{11}	s_{21}	s_{31}	s_{41}	s_{51}
2	s_{12}	s_{22}	s_{32}	s_{42}	s_{52}
3	s_{13}	s_{23}	s_{33}	s_{43}	s_{53}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
n	s_{1n}	s_{2n}	s_{3n}	s_{4n}	s_{5n}

Of course the parameters E_{Apij} to H_{Apij} and E_{Bpij} to H_{Bpij} for h_A and h_B participants are calculated previously using expensive data glove (parameters for another participant are also calculated). Then numerical formula for estimation of finger joint angles of the user is decided as following.

$$\theta_{upij} = E_{upij}S_i^3 + F_{upij}S_i^2 + G_{upij}S_i + H_{upij} \tag{15}$$

Also, we decide the $\boldsymbol{\mu}_{upn}$ according to the following formula.

$$\boldsymbol{\mu}_{upn} = \frac{(h_u - h_B)\boldsymbol{\mu}_{Apn} + (h_A - h_u)\boldsymbol{\mu}_{Bpn}}{h_A - h_B} \tag{16}$$

Where $\boldsymbol{\mu}_{upn}$, $\boldsymbol{\mu}_{Apn}$, and $\boldsymbol{\mu}_{Bpn}$ represent vector of sensor sample values of user, A, and B. The $\boldsymbol{\mu}_{upn}$ is used when using eq. 4. Using a weighted average of hand size, each parameter for estimation can be determined.

D. Equivalency of Variance-Covariance Matrix

When using eq. 4 to estimate hand motion, it is difficult to calculate the all parameters $\boldsymbol{\Sigma}_{pn}^{-1}$ directly for each user. So we investigated equivalency of variance-covariance matrix between different users by using Box's M Test. First of all, we got the sensor values when each participant performed representative hand motions. Each representative hand motion is performed n times. Table IV shows an example of the sensor values at the time t in motion p. Next, the average of the sensor values $\overline{s_i}$ for finger i is obtained by the following formula.

$$\overline{s_i} = \frac{1}{n}\sum_{j=1}^{n} s_{ij} \tag{17}$$

At this time, covariance of finger x and y, represented as V_{xy}, is obtained by eq. 18. And variance-covariance matrix $\boldsymbol{V}$ is defined as eq. 19.

$$V_{xy} = \frac{1}{n}\sum_{k=1}^{n}(s_{xk} - \overline{s_x})(s_{yk} - \overline{s_y}) \tag{18}$$

$$\boldsymbol{V} = \begin{bmatrix} V_{11} & V_{12} & \dots & V_{15} \\ V_{21} & V_{22} & \dots & V_{25} \\ \vdots & \vdots & \ddots & \vdots \\ V_{51} & V_{52} & \dots & V_{55} \end{bmatrix} \tag{19}$$

Then we decide V' according to the following natural logarithm (eq. 20).

$$V' = \ln \frac{|\boldsymbol{V}_{AB}|^{\nu_1+\nu_2}}{|\boldsymbol{V}_A|^{\nu_1}|\boldsymbol{V}_B|^{\nu_2}} \tag{20}$$

$$\nu_1 = n_A - 1 \tag{21}$$

$$\nu_2 = n_B - 1 \tag{22}$$

TABLE V
χ_0^2 OF EACH RESEARCH PARTICIPANT

	participant 1, 2	participant 2, 3	pariticpant 1, 3
Standard	22.44	28.64	28.84
Lateral Contact	29.34	36.22	20.87
Tripod	31.60	35.51	29.89
Parallel Ext	33.69	35.54	32.41

Where $\boldsymbol{V}_A$ and $\boldsymbol{V}_B$ represent mean variance-covariance matrix of participant A and B. The number of times n of participant A is different from B generally, each number is defined as n_A and n_B respectively. In this paper, each participant performs hand motion 10 times. And $\boldsymbol{V}_{AB}$ is the matrix obtained from the following formula.

$$\boldsymbol{V}_{AB} = \frac{\nu_1 \boldsymbol{V}_A + \nu_2 \boldsymbol{V}_B}{\nu_1 + \nu_2} \tag{23}$$

Also, we decide k according to the following formula.

$$k = 1 - (\frac{1}{\nu_1} + \frac{1}{\nu_2} - \frac{1}{\nu_1 + \nu_2}) \cdot \frac{2q^2 + 3q - 1}{6(q+1)} \tag{24}$$

Where q represents the number of explanatory variables. Now q is number of Thumb, Index, Middle, Ring, and Little finger, 5. Finally, we obtain test statistic χ_0^2 from the following formula.

$$\chi_0^2 = kV' \tag{25}$$

The χ_0^2 follows chi-squared distribution. We describe the χ_0^2 of each motion/user in Table V. We decide significance level α as 0.001. The $\chi^2(\alpha = 0.001)$ is 37.70. So if the χ_0^2 is smaller than 37.70, there is not significantly different in variance-covariance matrix. As Table V indicates, the χ_0^2 is smaller than 37.70 in all categories. We confirmed that there is not significantly different with regard to variance-covariance matrix. Thus we use the average matrix in variance-covariance matrix of all participants as $\boldsymbol{\Sigma}_{pn}$. Finally we can obtain the finger joint angles of new user.

IV. EXPERIMENTAL RESULT

We had an experiment to confirm the effectiveness of the method described above.

A. Experiment Environment

We had constructed two experiment systems, system A and system B.

1) System A: The system A estimates user's finger joint angles using same parameters for all users. These parameters were obtained by the hand of participant 2 because his hand size is mostly the same as average Japanese male's one.

2) System B: The system B estimates user's finger joint angles using parameters obtained by the user's own hand. User closes hand first, then each parameter is determined using H_{size}.

Both systems were used with the 5DT Data Glove 5 Ultra. They were implemented with C language, and the specification of PC is the following; CPU: Pentium (R) Dual-Core CPU E5200 2.50GHz. They draw CG image based on the obtained finger joint angles (Fig. 8). With the cooperation of two research participants 4 and 5, several hand motions were performed.

Fig. 8. Appearance of experiment

TABLE VI
ESTIMATED H_{size} OF PARTICIPANTS $[cm]$

	True H_{size}	Estimated H_{size}	Error
Participant 4	17.6	18.0	0.4
Participant 5	19.1	19.9	0.8

TABLE VII
JOINT ANGLE ERROR OF PARTICIPANT 4 IN SYSTEM A [DEGREE]

	Thumb	Index	Middle	Ring	Little	avg.
Standard	8.8	11.2	11.1	11.5	10.1	10.5
Lateral Contact	10.8	13.1	13.6	15.1	7.3	12.0
Tripod	18.6	10.6	13.5	11.5	17.5	14.4
Parallel Ext	10.4	13.4	8.8	9.0	10.3	10.4
Plastic bottle	15.2	10.7	15.3	20.2	9.9	14.3

B. Estimation Results

Table VI shows estimated H_{size} of two participants. An estimation error of participant 4 is 0.37, and the error of participant 5 is 0.79. The method can estimate user's H_{size} almost correctly. We confirmed the effectiveness of the H_{size} estimation method described in section III-B.

Table VII to X show the average of the errors of the finger joint angles between estimated finger joint angles and obtained angles by CyberTouch. Besides, "Plastic bottle" represents the hand motion as same as in section III-A.

These results indicate that the estimation accuracy of the system B is better than the system A. We had Student's t-test to these averages of the errors of each finger joint angles.

TABLE VIII
JOINT ANGLE ERROR OF PARTICIPANT 4 IN SYSTEM B [DEGREE]

	Thumb	Index	Middle	Ring	Little	avg.
Standard	6.5	6.3	3.6	15.0	18.4	10.0
Lateral Contact	12.0	11.7	11.4	11.4	8.7	11.0
Tripod	18.3	7.5	12.7	8.4	15.8	12.5
Parallel Ext	13.8	11.4	9.6	9.2	9.8	10.8
Plastic bottle	15.8	3.6	14.0	14.2	8.9	11.3

TABLE IX
JOINT ANGLE ERROR OF PARTICIPANT 5 IN SYSTEM A [DEGREE]

	Thumb	Index	Middle	Ring	Little	avg.
Standard	12.3	12.8	12.7	14.2	13.8	13.2
Lateral Contact	11.5	21.5	16.4	21.2	19.2	18.0
Tripod	10.2	8.2	12.8	22.9	17.6	14.3
Parallel Ext	24.0	9.2	4.3	7.6	13.6	11.7
Plastic bottle	23.2	13.6	16.2	31.0	20.8	21.0

TABLE X
JOINT ANGLE ERROR OF PARTICIPANT 5 IN SYSTEM B [DEGREE]

	Thumb	Index	Middle	Ring	Little	avg.
Standard	13.1	8.5	6.9	8.8	12.5	10.0
Lateral Contact	9.3	14.1	13.1	11.4	16.8	12.9
Tripod	9.4	7.7	18.8	19.0	17.5	14.5
Parallel Ext	13.0	8.8	16.0	10.8	13.5	12.4
Plastic bottle	26.1	10.3	20.8	13.4	11.0	16.3

TABLE XI
DIFFERENCE BETWEEN SYSTEM A AND B OF PARTICIPANT 4

	participant 4	
	difference	$P(T \leq t)$
Standard	-0.6	3.3×10^{-2}
Lateral Contact	-1.0	2.7×10^{-2}
Tripod	-1.8	3.9×10^{-2}
Parallel Ext	+0.4	1.6×10^{-1}
Plastic bottle	-3.0	6.7×10^{-3}
average	-1.2	-

TABLE XII
DIFFERENCE BETWEEN SYSTEM A AND B OF PARTICIPANT 5

	participant 5	
	difference	$P(T \leq t)$
Standard	-3.2	3.4×10^{-2}
Lateral Contact	-5.0	1.7×10^{-2}
Tripod	+0.2	4.0×10^{-2}
Parallel Ext	+0.7	8.1×10^{-1}
Plastic bottle	-4.6	1.0×10^{-2}
average	-2.4	-

Table XI and XII show the differences of the estimation accuracy between the system A and B, and p-values obtained from Student's t-test. It is statistical significance if the $P(T \leq t)$ is smaller than 0.05. They show that there is statistical significance about the hand motion of which estimation accuracy were improved. There is not statistical significance about Parallel Ext, but the estimation accuracy was not improved. Totally the system B is better than the system A, it means calibrated parameters for each user is effectiveness, and hand size estimation is needed.

V. CONCLUSION

In this paper, we proposed a method of hand size estimation and parameters calibration for finger joint angles estimation of low-priced data glove. The pilot system had been specified for specific user, and it could not been applied for any users. Our new system obtains user's hand size only from simple and easy task first, and parameters of estimation equations can be obtained automatically. Then a low-priced data glove can recognize the user hand motion, actually all finger joint angles. When a data glove becomes commercial popular, and VR applications will become commercial popular. VR technologies can provide extra work space.

The information about a hand is not only length from wrist to middle finger tip, however. In the future we would like to try to consider more detailed information of hand, for example, length of each finger, thickness, size of palm, and so on. We should also examine the effect for the angles estimation. And our system assumes grasping motion, so we would like to consider other hand motions like hand and finger signs.

ACKNOWLEDGMENT

We thank our colleagues in our laboratory for useful discussions. This work was supported in part by JSPS KAKENHI Grant Number 24501186.

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