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Development of a Measuring System of Contact Force during Braille Reading Using an Optical 6-Axis Force Sensor

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Abstract—**A system with an optical 6-axis force sensor was developed to measure contact force during braille reading. In using this system, we encountered two problems. One is a variability of output values depending on the contact point. This was solved by using two transformation techniques. The other is that subjects read braille in a different manner from the usual. We compared two manners of braille reading, one-handed vs two-handed, and found a small reduction in reading speed. Using this system, we collected data from four braille readers and quantitatively showed more minute contact force trajectories than those in earlier studies.**

I. Introduction

AMONG instructors of braille, raised tangible letters for the blind, it is said that highly skilled readers of braille only lightly touch the dots whereas less skilled readers press strongly. Also, skillful readers are said to maintain the contact force of fingers fairly constant whereas for unskilled readers it fluctuates greatly. Two earlier studies demonstrated these phenomena [1],[2]. However, the results were qualitative and force could not be quantitatively compared between experts and novices. In addition, the force-transforming apparatus used two pneumatic cylinders in Bürklen's study [1] and four springs under a plate in Kusajima' study [2], both along with a kymograph. They seem unable to respond quickly enough to the rapid change of contact force due to their physical properties. Hence, we have decided to adopt advanced force/pressure measurement technologies to perform quantitative and minute measurement of contact force.

Prior to this report, we had tested two measurement technologies. The first one was a small displacement sensor (DS2001-TS01, Japan System Development) with a spring around it [3]. This sensor and two shafts were placed beneath the measuring plate. The second one is called a surface pressure measurement system (I-SCAN, Nitta Corporation), and functions by means of pressure-sensitive conductive ink [4]. These two systems were proved to measure the contact force quantitatively and more minutely than the systems used in the earlier studies. However, periodic calibration over a period of weeks revealed their unstabe behaviors, thus our confidence in these quantitative data is low.

To obtain trustworthy pressure data, we have adopted, this time, an optical 6-axis force-torque sensor which is usually used in robot joints. We placed this sensor beneath the measuring plate on which the braille sheet is placed. To use this sensor, two problems must be solved. One is a variability of output values depending on the contact point. The other is that subjects read braille using one finger of one hand; this manner is different from the conventional two-handed manner. In this paper, we describe how we dealt with these problems to realize precise measurement of contact force. Also, sample data collected using this system are shown.

II. Measurement System Configuration

Fig. 1 shows the setup of the contact force measuring system. The optical 6-axis force sensor, OPFT-50N, Minebea Co., Ltd., was used to build the contact force measurement system. Its rating capacities are 50 N for f_x and f_y, 100 N for f_z, and 2.5 N·m for m_x, m_y, and m_z (***f*** and ***m*** denote force and moment, respectively). Our former experiments showed contact force during braille reading is, at most, around 1 N. Thus, it is desirable to use a force sensor whose capacity is of the same order as this value. However, such products cannot be found on the market. Hence, we opted to use the above sensor, the capacity of which is the smallest among existing products. The sensor is disc-shaped; its diameter is 50 mm and thickness is 31.5 mm. Its output is fed to a personal computer (PC) via a PCI board (OPFT-SCPCI, Minebea). The data acquisition software (OPFTD-01, Minebea), which is attached to the PCI board, was used in the calibration and experiment. According to the product specifications, the sensor itself can output data every 100 microseconds. The actual minimal period of using this software was 500 microseconds; the period was thought to depend on the

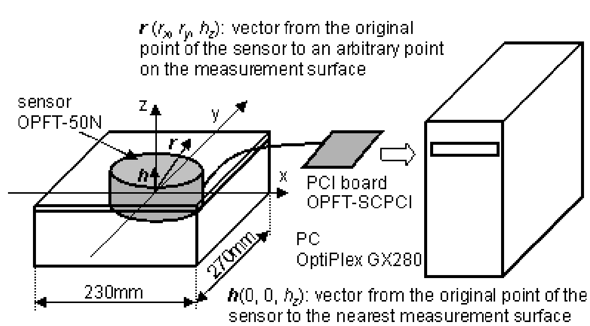

Fig. 1. Contact force measuring system.

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capability of the PC used (OptiPlex GX280 with Pentium4 processor540 and 512 MB memory, Dell).

A rectangular aluminum plate is fixed on the top face of the sensor. This plate is 270 mm long and 230 mm wide so that a B5-sized Braille sheet (257 mm × 182 mm), which is commonly used in Japan, can be placed on it. The thickness of the plate is 5 mm such that the plate does not yield to the contact force. The sensor is set in the center of the measuring plate. Beneath the sensor, an aluminum plate of the same size and thickness as the measuring plate is installed as the pedestal.

III. CALIBRATION AND CORRECTION

A. Periodical Calibration

The center of the measuring plate is used as the origin (0, 0) of *x*-*y* coordinates. A four-by-four grid pattern, 45 mm on one side, is drawn with its center set at the origin. Twenty-five nodes and edges of the grid pattern are used as calibrating points at which the weight is placed. The weight of 0.1 kgW is used since the contact force of skilled braille readers was around 1 N, as determined in our past research. Approximately two seconds after placing the weight on the plate, 6-axis data are recorded for two seconds or more at each of the 25 calibrating points. Data from the first two seconds are used to calculate the mean values.

Six calibrations performed over two months confirmed stability of f_z, m_x, m_y, and m_z and fluctuation of f_x and f_y. Although f_x and f_y are used to calculate contact positions, the effect of their fluctuation is limited because they are less than one-tenth of f_z (see Fig.2(a)).

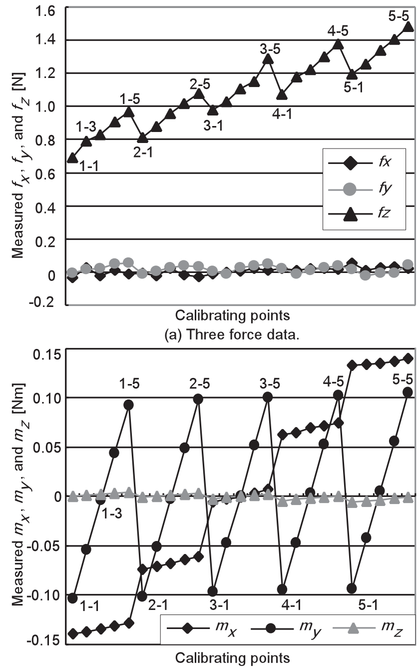
B. Correction of Vertical Force

Even when the same weight was loaded, f_z changed greatly depending on the calibrating point; the manufacturer of the sensor could not give a satisfactory account for this. The fluctuation falls in the range of accuracy of the sensor (5% R.O.). Nevertheless, from the practical aspect, it is more important that the relationship between the calibrating point and the output data be stable whatever the cause of fluctuation might be, and it was proven to be so. Thus, our concern now is to devise a method of estimating the true value by using measured data.

Fig. 2 shows 6-axis data fluctuation with the calibrating points. As f_z changes in proportion to the *x* and *y* coordinates, an affine transformation, which is a general first-order transformation, is thought to express f_z properly. Also, measurements with two different weights (0.05 kgW and 0.1 kgW) show that the change of 6-axis data with the calibrating points is proportional to the mass of the weight. Thus, we express the relationship between measured f_z and the expected value f_{ze} by the formula below, where *a*, *b*, and *c* are constants.

$$f_z = (ax_c + by_c + c) f_{ze} \quad (1)$$

f_{zi}, x_{ci}, and y_{ci} are obtained at 25 calibrating points. By substiuting these data into (1) and dividing both sides with f_{ze},



(a) Three force data.

(b) Three moment data.

Fig.2. Force and moment data measured at 25 calibrating points. "Number-number" in the figure denotes the calibrating point (Fig.2).

we obtain

$$\begin{bmatrix} f_{z1}/f_{ze1} \\ f_{z2}/f_{ze2} \\ \vdots \\ f_{z25}/f_{ze25} \end{bmatrix} = \begin{bmatrix} x_{c1} & y_{c1} & 1 \\ x_{c2} & y_{c2} & 1 \\ \vdots & \vdots & \vdots \\ x_{c25} & y_{c25} & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} . \quad (2)$$

Here, we express the 25×3 matrix as $\boldsymbol{A}$. By transforming (2) we obtain

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = A^{-1} \begin{bmatrix} f_{z1}/f_{ze1} \\ f_{z2}/f_{ze2} \\ \vdots \\ f_{z25}/f_{ze25} \end{bmatrix} = (A^t \cdot A)^{-1}\, {}^t A \begin{bmatrix} f_{z1}/f_{ze1} \\ f_{z2}/f_{ze2} \\ \vdots \\ f_{z25}/f_{ze25} \end{bmatrix} . \quad (3)$$

By substituting f_{zi}, f_{zei}, x_{ci}, and y_{ci} (i=1 to 25) into (3), we obtain *a*, *b*, and *c*. Once we have determined these constants, we can calculate f_{ze} by substituting the calibrating points (x_c and y_c) and measured f_z into (1). We compared f_{ze} calculated in this manner with the vertical force of the weight, 0.98 N (= 0.1 kg × 9.8 m/s^2), and found that the average error over 25 calibrating points is merely 1.3 %.

C. Correction of Contact Points

To correct f_z, contact points should be given. There is a method of computing contact points during reading braille from video images, but this method requires not only equipment such as video cameras (usually more than one) and analyzing software but also synchronization with contact force data. Another technique which uses only 6-axis force and moment data is also available [5]. This method does not require any equipment other than the 6-axis sensor. Hence, we selected this method.

When force $\boldsymbol{f}$ is applied at the contact point $\boldsymbol{r}=(r_x, r_y, r_z)$ on a rigid planar surface which is fixed onto the sensor, the following mechanics equation is derived.

$$\mathbf{r}=\frac{\mathbf{h}\times\mathbf{m}+(\mathbf{h}\cdot\mathbf{h})\mathbf{f}}{\mathbf{h}\cdot\mathbf{f}} \quad (4)$$

Here, $\boldsymbol{h}$ is the normal vector expressed as $\boldsymbol{h}=(0, 0, h_z)$, where h_z is the distance from the coordinate center of the sensor to the surface of the measuring plate, 20.75 mm. By substituting $\boldsymbol{h}$ into (4), we obtain

$$\mathbf{r}=\left(\frac{h_z f_x - m_y}{f_z}, \frac{h_z f_y + m_x}{f_z}, h_z\right). \quad (5)$$

The x-y coordinates calculated by inputting 6-axis data of the calibration into (5) and the actual calibrating points are shown in Fig. 4. Changes in f_z depending on the contact point yielded marked disagreements with actual calibrating points. The farther the point is from the center of the sensor, the larger the difference becomes. In the first and second quadrants, the difference is particularly large due to the smaller f_z values in the denominator in (5). The relationship between calculated and actual contact points seems to be a projective transformation. Actually, because m_x, m_y, and f_z exhibit aspects of linear transformation (Fig. 2), it is mathematically supported that $\boldsymbol{r}$ can be expressed as a projective transformation.

The projective transformation is expressed below, where r_x and r_y are true values and r_x' and r_y' are transformed values.

$$w\begin{bmatrix} r_x' \\ r_y' \\ 1 \end{bmatrix}=\begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix}\begin{bmatrix} r_x \\ r_y \\ 1 \end{bmatrix}=\mathbf{p}\begin{bmatrix} r_x \\ r_y \\ 1 \end{bmatrix}. \quad (6)$$

Unfolding (6) and eliminating w produces (7).

$$p_{11}r_x + p_{12}r_y + p_{13} - (p_{31}r_x + p_{32}r_y + p_{33})r_x' = 0$$

$$p_{21}r_x + p_{22}r_y + p_{23} - (p_{31}r_x + p_{32}r_y + p_{33})r_y' = 0$$

Inputting data for the 25 calibrating points in (7) generates 50 equations. The characteristic vector $\boldsymbol{p}$ with the minimal eigen becomes the solution of these equations. By expressing the inverse matrix of $\boldsymbol{p}$ with $\boldsymbol{q}$, we obtain

$$w\begin{bmatrix} r_x \\ r_y \\ 1 \end{bmatrix}=\mathbf{q}\begin{bmatrix} r_x' \\ r_y' \\ 1 \end{bmatrix}=\begin{bmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{bmatrix}\begin{bmatrix} r_x' \\ r_y' \\ 1 \end{bmatrix}. \quad (7)$$

By unfolding (7), corrected values of contact points can be obtained as

$$r_x=\frac{q_{11}r_x'+q_{12}r_y'+q_{13}}{q_{31}r_x'+q_{32}r_y'+q_{33}}, r_y=\frac{q_{21}r_x'+q_{22}r_y'+q_{23}}{q_{31}r_x'+q_{32}r_y'+q_{33}}. \quad (8)$$

Superimposing the corrected contact points onto actual points proved the validity of the correction (Fig. 5). The average error in the distance between corrected and actual points is merely 1.7 mm.

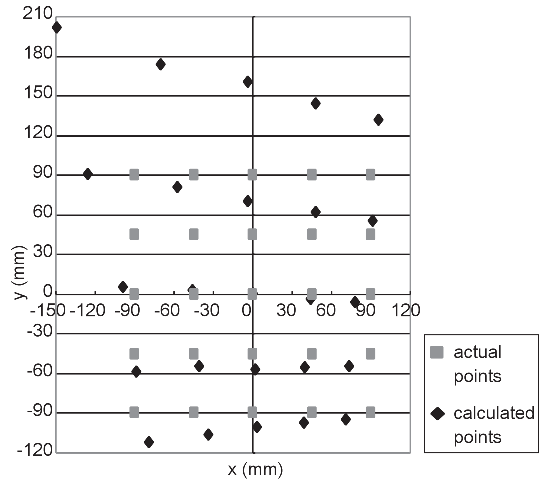


Fig.3. Calculated contact points superimposed on the actual points.

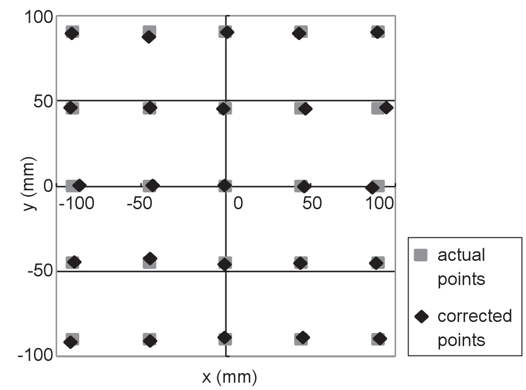


Fig.4. Corrected contact points superimposed on the actual points.

IV. Comparison of Reading Speed between One-Handed and Two-Handed Reading

Due to the restriction of the measurement system, subjects must read braille with one finger of one hand. This unusual manner of reading was compared with the conventional reading manner (two-handed reading in many cases) from the viewpoint of reading speed.

A. Subjects

Subjects were eight visually impaired persons who use braille in everyday life except subject H; he learned and used braille in his high school days but now relies mostly on screen readers to access information. Also, subject G has rheumatism and claimed her reading speed might be slower at the time of experiment than ever before. Subjects' attributes are shown in Table 1.

B. Procedure

The subject sat on a chair in front of a desk on which reading materials were placed. Braille sheets were displayed page by page. The first five/six sheets were read silently in the usual manner (mostly using both hands) and then another five/six sheets were read silently using one finger of one hand. The start of reading was signalled by the experimenter. The subjects were requested to report it aloud when they finished reading. The experimenter also verified the end of reading by observing the subject's reading finger. Reading time was measured with a stopwatch. Movements of the fingers were recorded with a digital video camera.

TABLE I
PARTICIPANTS IN READING SPEED TEST

Subjects	Sex	Age at Testing (years)	Length of Braille Use (years)	Hands Usually Used	Dominant Hand in Braille Use
A	female	20	16	Both	Left
B	male	21	16	Both	Left
C	female	19	13	Both	Right
D	male	18	7	Both	Left
E	male	20	5	Right	Right
F	male	29	24	Both	Left
G	female	60	50	Both	Right
H	male	30	14	Left	Left

For both manners of reading, subject A and B read six sheets and subjects C to H five sheets. As subject H read braille more slowly than other subjects, shorter sentenses were presented to him.

C. Result

Braille reading speed was calculated by dividing the number of braille letters by the reading time. Then the average was computed over five/six sheets separately for the two reading manners.

The fastest reader, subject C, read at a speed of 10.9 letters per second. She finished one braille sheet in about 40 s. In one minute, she can read more than 600 letters; this speed is more than two times practical braille reading speed, 250 letters per second [6]. Other subjects, except for Subjects G and H, also finished each sheet within approximately one minute, indicating that they have practical braille reading ability.

Fig.6 shows the reading speeds of one-handed and two-handed reading. One-handed reading is slower than two-handed reading by only 10 to 20 percent. However, this reduction is thought to be due to the time used to find the heads of lines with the reading hand. In the usual reading manner, the left hand performs this task while the right hand is reading the previous line. Thus, we assumed that contact of the finger to the braille itself would not be different in the one-handed reading manner.

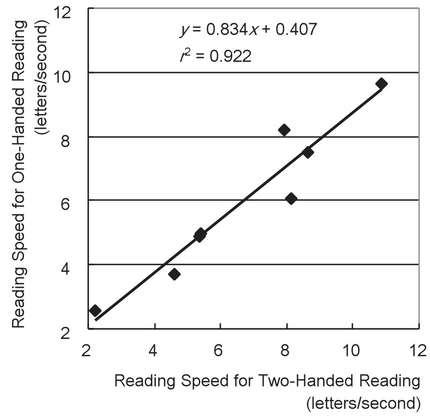


Fig.5. Reading speeds for one-handed and two-handed reading (n=8).

V. MEASUREMENT OF CONTACT FORCE

A. Subjects

The subjects were four blind persons listed in Table 1 as Subjects E, F, G, and H.

B. Procedure

The subject sat on a chair in front of a desk and silently read the braille sheet on the measurement system. Six-axis data were recorded with the sampling frequency of 65 Hz. Two video cameras recorded the movements of the subject's fingers from the top and the side. The side image is used to verify that the fingertip was touching the braille dots. The system was calibrated either before or after each experiment.

C. Result

Data correction consists of three steps. Firstly, constants for the inverse affine and projective transformations were calculated using the calibration data. Secondly, the contact points were computed from 6-axis data during Braille reading and were corrected using the inverse projective

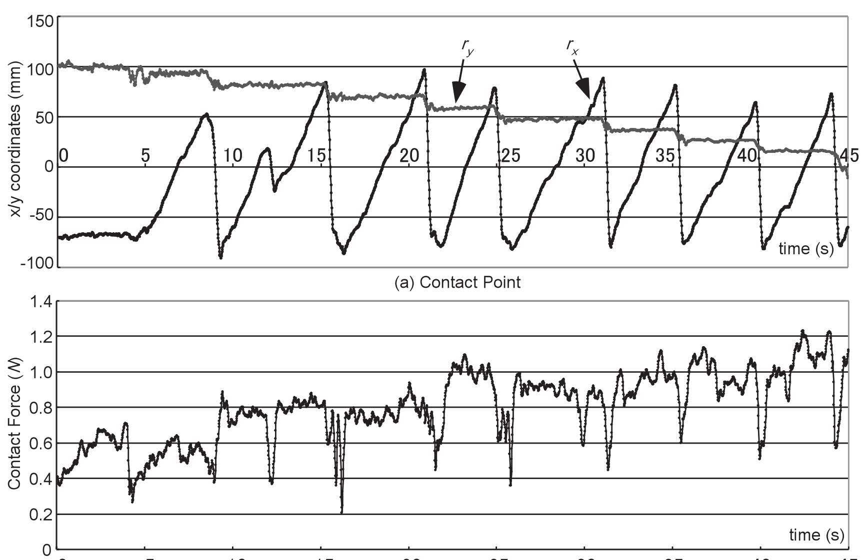


Fig.6. Contact points and pressure when subject E was reading a line of Braille.

transformation. Trajectories of the contact points were compared with the arrangements of braille dots on the sheet and the video images taken during the experiment. Thirdly, f_z was corrected using the inverse affine transformation.

Fig. 6 shows the movement of the finger and the contact force when subject E read a sheet with one finger. In Fig. 6 (a) a sawtooth wave for corrected r_x and a steplike wave for corrected r_y can be seen. In Fig. 7 (b) a series of trapezoids can be observed. Tops of trapezoids correspond to the flat steps of r_y and oblique lines of r_x. The combination of these waves indicates that the reader's finger moved at a constant velocity in the horizontal direction and the contact force fluctuated while reading one line. Also, steep-sided valleys between rough tops of trapezoids were observed; they correspond to the sweeping of fingers from the end of the previous line to the head of a new line. These fluctuations of contact force in one line and a sharp decrease of pressure during sweeping movements were observed quantitatively for the first time in this study.

VI. Discussion

A. Measurement with 6-axis sensor

In Fig. 6 we can see that the first few steps of r_y fluctuate more greatly than other steps and f_z in the first few lines are smaller than in later lines. If we compare constants in $\boldsymbol{q}$ in (8), we can see that q_{11}/q_{12}=29.6 and q_{22}/q_{21}=17.9. This means that corrected r_x and r_y are most affected by r_x' and r_y' calculated with (5), respectively. Therefore, let us examine (5). As f_z is the denominator, the fluctuation of f_z leads to an amplified fluctuation of $\boldsymbol{r}$ when f_z is less than one, that is, when contact points are on the upper area of the measuring plate. Therefore, for more precise correction of contact movements and pressure, it is recommended that the measurement be carried out in the vicinity of the sensor. Actually, that is what we did in the experiment with subject F.

B. Reading Manner

To ensure that one-handed reading would not affect the contact mode of the finger to the braille dots, line-by-line timing is necessary. We are planning to measure it using the video images taken in the experiment.

Even if there is a difference between the two reading manners, the contact force data themselves are meaningful in that they indicate the subjects were able to read the braille dots with that force. To determine the quantitative difference in force between skilled and unskilled braille readers, further study should be carried out with a larger group of subjects having various braille reading abilities.

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