Relative Position Calibration between Two Haptic Devices Based on Minimum Variance Estimation

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Abstract. In this paper, we propose a new method to estimate the relative positions of multiple haptic devices. As is the case in stereo camera calibration, the accurate measurement of the relative positions of haptic devices is difficult. The proposed method uses the acquired stylus positions of two devices and estimates the relative positions of two devices based on minimum variance estimation. In this method, the data acquisiton process has been improved to allow a large number of data points to be easily acquired. We conducted preliminary experiments to estimate the positions of two devices. The results showed the feasibility and reasonable accuracy of the proposed method.

Keywords: Haptics, Calibration, Positioning.

1 Introduction

In recent years, various haptic display devices has been developed and utilized in several practical applications such as surgical and dental simulators [1, 2]. We also constructed a smart but cheaper dental surgical simulation system [3]. In dental operations, dentists simultaneously use multiple tools such as a dental bar, mirror, pick, and vacuum. For this reason, our system is prepared for the use of multiple haptic devices in parallel. For effective and practical operation, it is preferable to allow the arrangement of devices to be changed based on the operation, working situation, or size of user's hand. However, the accurate measurement of the relative positions and attitudes of the haptic devices is a difficult and troublesome task, just as with stereo camera calibration. Therefore, once the device arrangement is initially fixed, it is rarely changed, but is continually as is, with the exception of some extraordinary circumstance.

In a multiple haptic device environment, it is important to know the relative positions and attitudes of the devices. We have been studying the calibration method in various situations [4, 5]. In our previous method [5], these properties were calculated by solving redundant simultaneous equations using data derived from several

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identical end-points of the two devices. It was found that the accuracy of the calibration was improved by increasing the quantity of end-point data that was stored. However, in the previous method, the data acquisition process was very complicated, and the maximum number of data points was only 24.

In this paper, we propose a new method to estimate the relative positions of multiple devices based on minimum variance estimation. In this new method, the data acquiring process has been improved, and a large number of data points can be easily acquired. The use of this new method is expected to improve the estimation accuracy. Preliminary experiments were conducted, and the results showed the feasibility and reasonable accuracy of the proposed method.

2 Methodology

$\boldsymbol{p}_{ri}$ and $\boldsymbol{p}_{li}$ are the position vectors of the end effectors of two haptic device in individual local coordination systems Σ_r and Σ_l, as shown in Fig. 1.

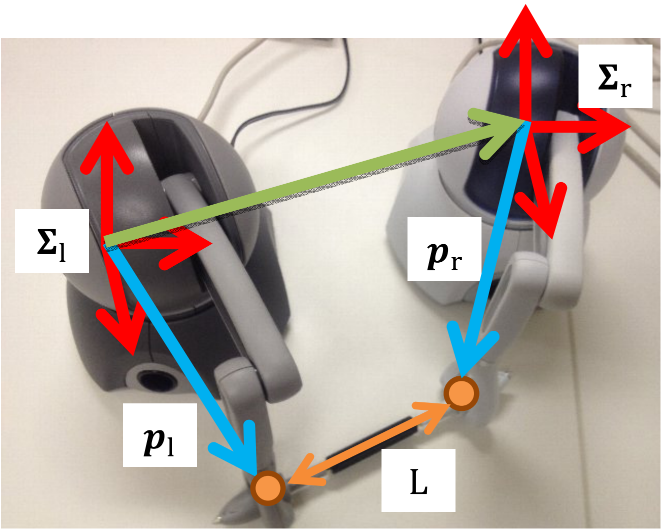

Fig. 1. Coordinate systems

$$\boldsymbol{p}_{ri} = (x_{ri}\ y_{ri}\ z_{ri})^T$$
$$\boldsymbol{p}_{li} = (x_{li}\ y_{li}\ z_{li})^T$$
$$i = 1, 2, 3, \ldots, n$$

L_i is the distance between two end effectors in a world coordinate system. It can be calculated by

$$L_i = \| \boldsymbol{p}_{ri} - \boldsymbol{p}_{li} + \boldsymbol{p}_d \|$$

where $\boldsymbol{p}_{\mathrm{d}} = (\mathrm{x_d}\ \mathrm{y_d}\ \mathrm{z_d})^{\mathrm{T}}$ is the relative position vector of both devices.

Here, V is defined as the variance of $\mathrm{L_i}$,

$$\mathrm{V} = \frac{1}{n}\sum(\mathrm{L_{ave}} - \mathrm{L_i})^2$$

where $\mathrm{L_{ave}}$ is the average of $\mathrm{L_i}$. In the world coordinate system, $\mathrm{L_i}$ should be the constant value because both devices are fixed; as a result, V becomes 0 in theory. Practically, V becomes close to 0. Then, under this constraint, $\boldsymbol{p}_{\mathrm{d}}$ can be searched using a minimum variance estimation, $\mathrm{argmin(V)}$.

3 System Setup

Two haptic devices (PHANToM OMNI, SensAble Technologies) were used for the following verification experiment. To acquire the position data $\boldsymbol{p}_{\mathrm{ri}}$ and $\boldsymbol{p}_{\mathrm{li}}$, the two devices were physically connected using a rigid connecting bar (Fig. 2). The connecting bars were fabricated from plastics using a 3D printer (3D Touch, Bits From Bytes), and 6.35 [mm] stereo female jacks were mounted at the ends of each bar (Fig. 3). The two devices were connected to a laptop PC (EliteBook 8440w, HP) by IEEE1394 through an interface board (1394a2-EC34, Kuroutoshikou). An estimation program was created using Microsoft Visual Studio 2008 Professional Edition. For the minimum variance search, a brute-force calculation was applied at 1 [mm] along each axis. To search a 100 [mm^3] area, it took approximately 10 [s].

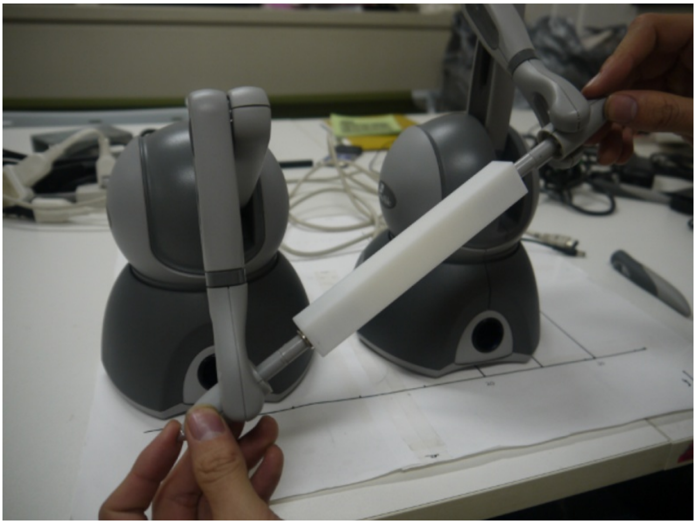

Fig. 2. Two haptic devices connected by connecting bar

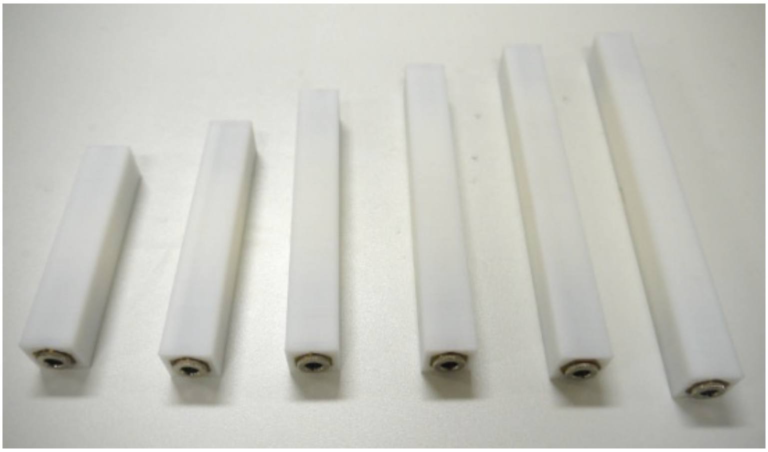

Fig. 3. Various lengths of connecting bars (100, 120, 140, 160, 180 and 200 [mm])

4 Experiment and Results

The horizontal displacement values $\mathrm{x_d}$, $\mathrm{y_d}$, and $\mathrm{z_d}$ were set visually to 250 [mm], [mm], and 0 [mm], respectively, by using a steel ruler (Fig. 4). The search range of $\boldsymbol{p}_{\mathrm{d}}$ was set to $200 < x < 300, 0 < y < 100, -50 < z < 50$ for 1 [mm] sampling. By moving the connector randomly while measuring $\boldsymbol{p}_{\mathrm{r}}$ and $\boldsymbol{p}_{\mathrm{l}}$, a large number of data points easily obtained. Fig. 5 shows the 3D plotted graph of $\boldsymbol{p}_{\mathrm{r}}$ (red dots) and (green dots) when a 200 [mm] long bar was used. The number of data points for each experiment is shown in Table 1.

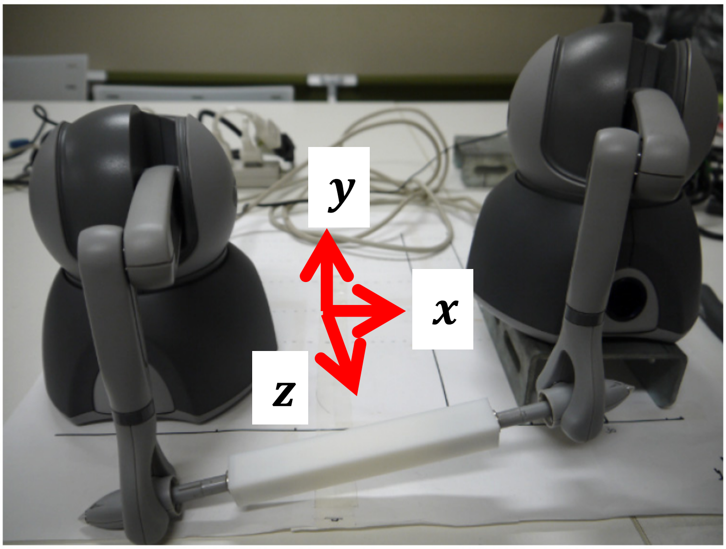

Fig. 4. Experimental condition $(\mathrm{x_d} = 250, \mathrm{y_d} = 50, \mathrm{z_d} = 0)$

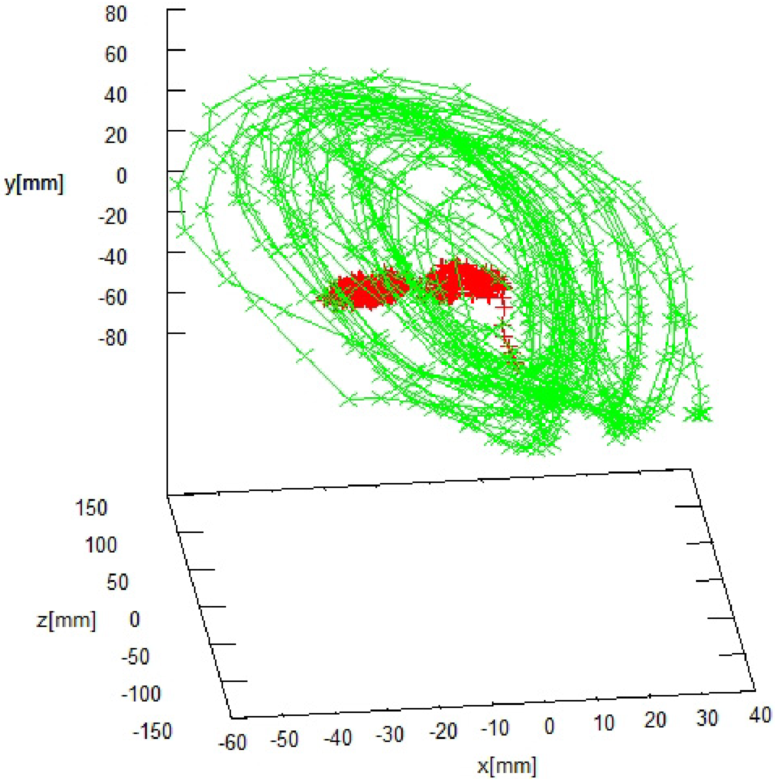

Fig. 5. Acquired data of $\boldsymbol{p}_{\mathrm{r}}$ and $\boldsymbol{p}_{\mathrm{l}}$ (number of data points $\mathrm{n} = 690$)

Fig. 6 shows the results for the estimated relative position, and Table 1 lists the detailed values of the results. The estimated values are approximately the same regardless of the bar length, and all $\mathrm{V_{min}}$ values are quite low. This result shows the feasibility of the proposed method. Note that it is a matter of no importance that the estimated results shown in Table 1 differ from the experimental condition ($\mathrm{x_d} = 250, \mathrm{y_d} = 50, \mathrm{z_d} = 0$). These are not true values, but are only reference values.

Fig. 7 shows the variation in $\mathrm{L_i}$. The red and blue lines show $\boldsymbol{p}_{\mathrm{d}} = (0\ 0\ 0)^{\mathrm{T}}$ and $\boldsymbol{p}_{\mathrm{d}} = (241\ 51\ \ -7.0)^{\mathrm{T}}$, respectively. As can be seen, the variance of the blue line is flat and almost exactly zero.

Fig. 8 shows the variation in V, which is calculated in the range of $200 < \mathrm{x_d} < 300,\ 0 < \mathrm{y_d} < 100,\ and\ \mathrm{z_d} = 0$. The dark color indicates a low value of V. As can be seen, the graph has a local minimum of $\mathrm{x_d} = 250,\ \mathrm{y_d} = 50$, and the minimum point is the estimation result for relative positions of the two devices, $\boldsymbol{p}_{\mathrm{dmin}}$.

Table 1. Results of relative position estimation

Bar length [mm]	argmin(V)			V_{min}	Number of data points
	x_d [mm]	y_d [mm]	z_d [mm]		
100	238	49	-3	0.144	773
120	240	50	-4	0.278	741
140	240	50	-7	0.163	745
160	240	50	-7	0.180	759
180	247	53	-8	0.166	770
200	241	51	-7	0.113	690

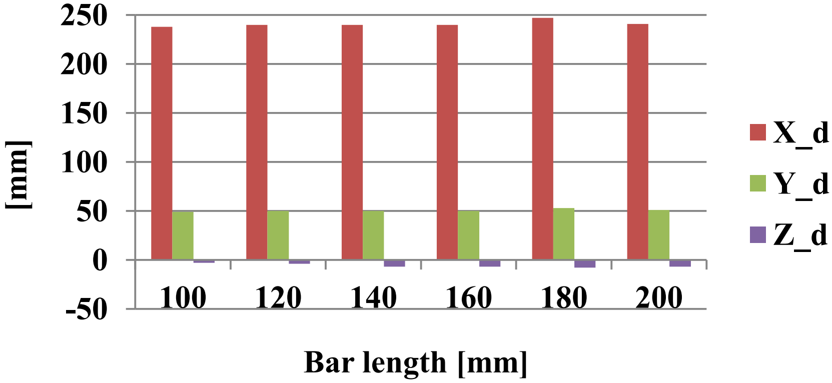

Fig. 6. Results of estimation

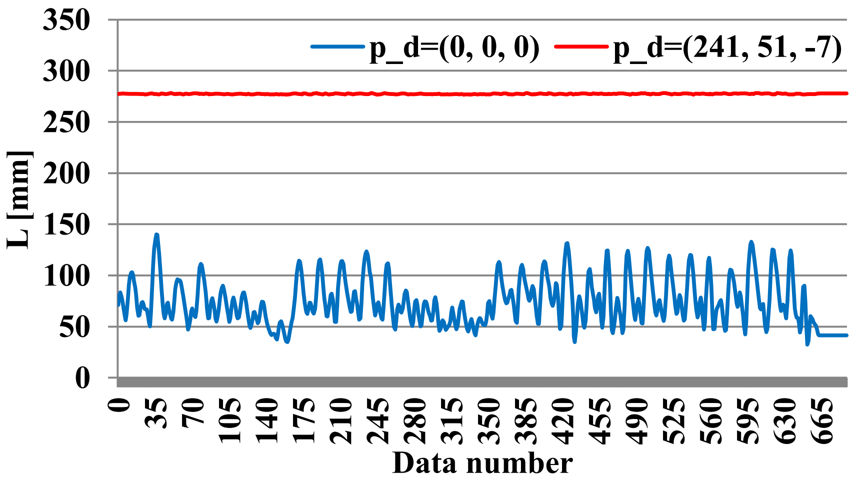

Fig. 7. Variation in L_i (blue: $\boldsymbol{p}_d = (0\ 0\ 0)^T$, red: $\boldsymbol{p}_d = (241\ \ 51\ \ -7)^T$)

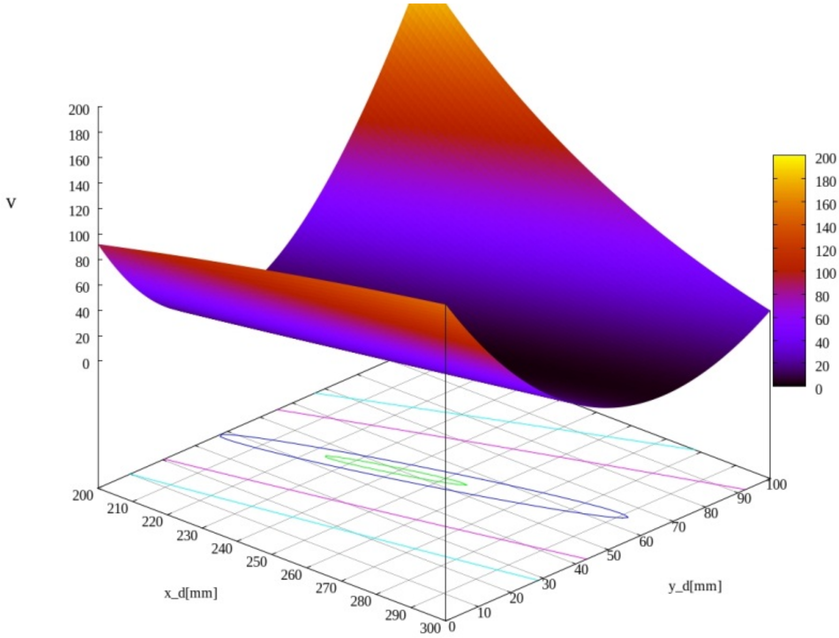

Fig. 8. Variation in $V\,(200 < x_d < 300, 0 < y_d < 100,\ z_d = 0)$

5 Conclusion

In this paper, we proposed a new method for estimating the relative positions of two haptic devices. Preliminary experiments to estimate the positions of two devices were conducted, and the experimental results showed the feasibility and reasonable accuracy of the proposed method. It was also revealed that the results had some estimation error. In this research, we only took into account the relative positions, which may have caused estimation error. In future research, we will consider the relative orientations of the devices. To reduce the calculation time, we will also introduce a search algorithm such as the steepest descent method.

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