Operating method of three-dimensional positioning device using moving characteristics of human arm

Masaharu KOMORI*, Takayuki UCHIDA*, Koji KOBUYASHI* and Tatsuki TASHIRO*
* Department of Mechanical Engineering and Science, Kyoto University
Kyotodaigakukatsura, Nishikyo-ku, Kyoto-shi, Kyoto 615-8540, Japan
E-mail: komorim@me.kyoto-u.ac.jp

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Abstract
When three-dimensional positioning devices such as a robot arm are operated, it is desirable for the devices to be operated by humans without the need for prior practice. The operating method in which the operator moves his/her arm and the device performs the same motion is a possible method. However, a difference may exist between the intended arm motion of the operator and the actual motion. In such a case, the positioning device performs the unintended than the intended motion of the operator. Therefore, in this study, the difference between the intended arm motion of the operator and the actual motion was investigated experimentally, supposing that the operator operates the device by his/her arm motion. The experimental results revealed that the operator tends to move the wrist joint center along a curve even though he/she intends to move it linearly. As an example, if the operator intends to move the wrist position straight in the right and left directions or the up and down directions, the actual wrist position tends to move along a curved path convex to the far direction. By considering the observed difference between the intended arm motion and the actual motion, an operating method was established. This method uses conversion equations to calculate the intended arm motion of the operator from the measured data of actual arm motion. In another experiment, operations using the new conversion equations and the conventional operation method were carried out. The results were compared and the effectiveness of the proposed method was confirmed.

Keywords : Operation, Three dimensional position, Human arm, Arm motion, Positioning device, Robot

1. Introduction

Robots are used in diverse fields such as manufacturing (Mizukawa and Koyama, 1999) and welfare (Exact Dynamics website, 2017). Devices such as the arms of robots are capable of moving in space with multiple degrees of freedom. The operation of a robot arm is generally conducted by an operating device with buttons or levers that issue commands for moving in the X, Y, and Z directions (Mizukawa and Koyama, 1999; Le et al., 2014). It is necessary for the operator to understand how the robot moves when each button or lever is pushed. Therefore, practice and experience are essential. In the future, however, it is expected that many robots and moving devices will be used in fields of life support and welfare, and it is assumed that users will have little knowledge about their operation. Given that condition, it is desirable that the devices be able to be intuitively operated without reading a manual and without prior practice (Kato and Yamashita, 1986).

The master-slave system for robot arm movement is an easy intuitive operating method. In this system, when the operator moves the master using his/her arm, the robot as the slave performs the same movement. Therefore, it is easy for the user to understand the correspondence between the movement of the master and that of the slave. These movements are possible because the arms of humans and the robots under consideration have multiple degrees of freedom. By combining the motion of the shoulder joint and that of the elbow joint, it is possible for humans to change arm positions in space. Many studies on master-slave systems have already been carried out (Jariyawattanakul and Maneewam, 2014; Lee et al., 2014; Luo et al., 2009; Rebelo et al., 2014; Zheng et al., 2013).

In the last few years, the use of non-contact motion measurement sensors is spreading, and it has become easier to
measure the motion of a human arm with no contact (Ionescu et al., 2014; Shinomiya et al., 2014). In some studies, the motions of the hand or arm for operating a device by gestures have been measured by a non-contact sensor (Devine et al., 2016; Ganapathyraju, 2013; Grzejszczak et al., 2012; Hoshino et al., 2006; Mao et al., 2016; Pyo et al., 2011; Rashid and Han, 2016). In some methods, the operator moves his/her arm and the robot or the device performs the same motion by using non-contact motion measurement sensors (Arango et al., 2013; Fuad, 2015; Grafhoff et al., 2016; IEEE Spectrum website, 2017; Qian et al., 2013; Shirwalkar and Singh, 2013). Because it is easy to understand the correspondence between the motion of the arm and that of the robot, such operating methods are thought to be easy and intuitive. On the other hand, because the robot exactly traces the arm motion of the operator in this method, the operator must move his/her arm accurately to operate the device accurately. However, it is not confirmed whether the actual arm motion of the operator agrees with the intended motion when the operator moves his/her arm to operate a robot, and the intended arm motion of the operator and the actual motion might be different. In addition, the accuracy of the operator actually moving his arm has not been clarified. It is supposed that it is possible to move the arm with a higher level of accuracy under the condition that the operator moves the arm carefully. However, if the operation time is limited and it is not possible to pay enough attention to the motion of the arm, the motion accuracy of the arm might be low. In other words, there is a possibility that the motion of the arm becomes more natural when not enough attention is paid to the motion. In this case, a slave robot would perform a different motion from the intended motion of the master operator.

This study supposes a case in which the three-dimensional position of a moving device such as a robot is operated by following the arm motion of the operator and investigates how accurately the operator moves his/her arm in the intended motion. The differences between the intended arm motion of the operator and the actual arm motion, and the motion characteristics of the arm when the arm motion is used for operation are clarified in an experiment. After identifying the differences between the intended motion of the operator and the actual motion of the arm, an operating method is proposed. This method uses equations to convert the actual arm motion of the operator to the intended motion. Finally, an experiment is carried out in which operation is performed using the established converting equation, and its effectiveness is confirmed.

2. Experiment to investigate the characteristics of arm motion for moving an object

In this section, an experiment is carried out to clarify the relation between the intended arm motion of the operator and the actual arm motion. The experiment supposes an operator (participant) moving the position of an object by his/her arm motion. The participant watches the motion of the object and actually moves his/her arm while intending a specific arm motion corresponding to the required arm motion to operate the object according to the observed motion. The actual arm motion is measured, and the correspondence with the motion of the object is investigated.

2.1 Definitions of basic posture, coordinate system, axes, points, and areas

To measure the motions of the arm and the object, definitions of coordinate systems, axes, points, and related areas are given. The right arm is used in this study.

Basic posture: As shown in Fig. 1(a), a participant sits on a chair and stretches his/her back, positions his/her upper arm in the vertical down direction and his/her forearm in a horizontal forward direction with the elbow joint bent at 90 degrees. This state is called the “basic posture” for operating an object.

Wrist basic position: As shown in Fig. 1(a), this is the position of the wrist joint center in basic posture, and it becomes the center of the wrist motion area described later.

Shoulder-joint-centered coordinate system: As shown in Fig. 1(b), this is a right-handed rectangular coordinate system fixed at the shoulder of the operator. Its origin is the shoulder joint center $S$, and the three orthogonal axes are $X$, $Y$, and $Z$. The $X$-axis is on a straight line through the right and left shoulder joint centers of the operator, and the positive direction of the $X$-axis is the direction from the left shoulder joint to the right shoulder joint. The $Z$-axis is perpendicular to the seat of the chair (vertical direction), and the positive direction is upward. The $Y$-axis is perpendicular to the $X$- and $Z$-axes, and the positive direction is the forward direction of the operator.

Wrist motion coordinate system: As shown in Fig. 1(b), this is a right-handed rectangular coordinate system fixed to the space. The origin is the wrist basic position, and the three orthogonal axes are $X_w$, $Y_w$, and $Z_w$. These axes are parallel to...
the X-, Y- and Z-axes of the shoulder-joint-centered coordinate system, respectively.
Wrist motion area: As shown in Fig. 1(b), this represents the moving area of the wrist joint center. This area is inside a cube that is 300 mm on each side. The center of gravity is the wrist basic position. The range is \(|X_w| \leq 150\, \text{mm}, |Y_w| \leq 150\, \text{mm}, |Z_w| \leq 150\, \text{mm}\) in the wrist motion coordinate system. The wrist motion area is smaller than the movable area of the arm of an adult and it is assumed that the operator can move his/her arm easily within this area.
Imaginary controlled object: It is assumed that the operator moves this object. The object is in a virtual space that is displayed on a screen.
Center of motion area of imaginary controlled object: As shown in Fig. 1(c), this is the center of the motion area of the imaginary controlled object described later.
Coordinate system for motion of imaginary controlled object: As shown in Fig. 1(c), this is a right-handed rectangular coordinate system fixed to the space (virtual space on a screen). Its origin is the center of motion area of the imaginary controlled object, and the three orthogonal axes are \(X_o\), \(Y_o\), and \(Z_o\). These axes are parallel to the \(X\)-, \(Y\)- and \(Z\)-axes of the shoulder-joint-centered coordinate system, respectively. The position of the imaginary controlled object is defined by this coordinate system.
Motion area of imaginary controlled object: As shown in Fig. 1(c), this is the moving area of the imaginary controlled object.

![Diagram](image_url)

Fig. 1 Definitions of basic posture, coordinate systems, and areas

2.2 Experimental method
2.2.1 Overview of experimental method

As shown in Fig. 2, a participant sits in the basic posture and faces the display screen. The participant assumes that he/she is operating the imaginary controlled object in the virtual space displayed on the screen at his/her wrist joint center, and moves his/her arm so that the motion is appropriate for the motion of the imaginary controlled object. In other words, the participant intends to move his/her arm so that the motion of his/her wrist joint center is the same as that of the imaginary controlled object. The actual arm motion is measured under this condition. It is assumed that the motion of the imaginary controlled object reflects the intended arm motion of the participant. The relation between the intended arm motion and the actual arm motion is investigated. The motion is measured using real-time motion capture.

2.2.2 Imaginary controlled object and its motion

When observing the imaginary controlled object in virtual space, the visual information obtained from the virtual space should be similar to that obtained from the real world. Figure 3(a) shows the constructed virtual space. The blue circle is the imaginary controlled object. The black lines and the black broken lines compose a cube. The inside of this cube is the motion area of the imaginary controlled object. On the screen, the size of the small “far” square, shown by the black broken lines, is 54 mm by 54 mm, and that of the large “close” square, shown by the black lines, is 90 mm by...
90 mm. As shown in Fig. 3(b), the center of the motion area of the imaginary controlled object (the origin of the coordinate system for motion of the imaginary controlled object) is the same as the center of gravity of this cube. The $X_o$-axis of the coordinate system for motion of the imaginary controlled object is parallel to the normal vector of the right and left faces, the $Y_o$-axis is parallel to the normal vector of the far and close faces, and the $Z_o$-axis is parallel to the normal vector of the upper and lower faces.

It is assumed that it is difficult to perceive the depth position in this virtual space because this virtual space is displayed on a flat screen. To address this problem, as shown in Fig. 3(c), the diameter of the circle is enlarged when the imaginary controlled object is close, and it becomes smaller when the imaginary controlled object is far. Furthermore, to make it easier to perceive the depth position, the blue broken lines indicating the depth position of the imaginary controlled object (i.e., intersecting line between the vertical and horizontal four faces and $X_oZ_o$ parallel plane
including the position of the imaginary controlled object) are drawn on the vertical and horizontal four faces.

![Diagram of motions](image)

**Fig. 4** Motions of imaginary controlled object shown to participant

In the experiment, the imaginary controlled object moves along 25 courses, shown in Fig. 4. The coordinate system in Fig. 4 is the coordinate system for motion of the imaginary controlled object, and the cube is the motion area of the imaginary controlled object. The light blue arrows are the courses. To easily recognize diagonal motion, the plane including the course is shown in yellow. The imaginary controlled object begins its motion from the center position of the course, reaches one end of the course and then the other end, and goes back to the center position of the course. This series of motions is counted as one round trip. The imaginary controlled object makes one round trip in approximately six seconds, and makes eight round trips in total. The motion is shown to the participant in the order from motion 1 to motion 25. Therefore, each participant performs eight round trips for each of the 25 motions.
2.2.3 Measurement of arm motion

(1) Experimental setup

As shown in Fig. 2, the operator sits on a chair and moves his/her arm while intending to operate the imaginary controlled object on the screen. The motion of the arm is measured by the real-time optical motion capture system MicronTracker (H3-60 model, from Claron Technology Corporation). MicronTracker tracks the marker in the measurement area with a camera, and it can acquire the position and posture in real time. The motion of the arm is calculated from the measurement result of the position and the posture of the marker attached to the operator. First, the position of the wrist joint center of the participant sitting in the basic posture is measured, and thereafter the motion of the arm is measured.

(2) Instructions and practice

It is explained to each participant that the \( X_c \), \( Y_c \), and \( Z_c \)-axes of the shoulder-joint-centered coordinate system and the \( X_r \), \( Y_r \), and \( Z_r \)-axes of the coordinate system for motion of the imaginary controlled object are in the same direction (see Fig. 1). With that in mind, the participant is instructed to move his/her right arm intuitively according to the motion of the imaginary controlled object under the assumption that he/she is operating it by his/her right wrist. Before the experiment, the participant is instructed to identify the wrist motion area. It is explained to the participant that the cube on the screen (Fig. 3) is the motion area of the imaginary controlled object and the position of the wrist in the basic posture corresponds to the center of the cube on the screen. In addition, the wrist motion area is visualized by using a 300 mm ruler as follows. When the participant is in the basic posture, the central part of the ruler (near 150 mm) is put on the wrist of the participant, and it is explained that the area from 0 mm to 300 mm is the wrist motion area. The ruler is put in the vertical, horizontal, and depth directions to show the complete wrist motion area. In addition, it is explained that the length of one side of the cube on the screen corresponds to the length of the 300 mm ruler. The participant is instructed to move his/her wrist position beyond the edge of the ruler when the imaginary controlled object is on the edge of the cube. Under these conditions, the participant is instructed to move his/her arm freely until he/she recognizes the size without seeing or touching the ruler. After the participant recognizes the wrist motion area by these exercises, the ruler is taken away and the experiment is performed. The participants are five adults without disability or injury in the right arm. This experiment and the experiment in section 4 were conducted with the approval of the Ethics Committee, Graduate School of Engineering, Kyoto University.

2.3 Experimental results

The position of the wrist joint center in the wrist motion coordinate system was calculated from the measurement data. Figure 5 shows the path of the wrist joint center of one participant. Although the imaginary controlled object makes eight round trips for one motion in the experiment, Fig. 5 shows the path for 3.5 round trips, from the 2nd round trip to the 7.5th round trip. The arm motions of the participants may not be stable in the beginning and the end of the motion of the imaginary controlled object, so these trips are removed from the path observations. In Fig. 5, the paths projected to the \( X_aY_a \) plane and the \( Y_aZ_a \) plane are shown. The paths are bunched together in each graph and they are the paths of the wrist joint center for 3.5 round trips.

Figure 5(a) shows the paths of the wrist joint center of one participant when the imaginary controlled object moves in motions 1, 2, and 3. In other words, the object moves parallel to the \( X_c \), \( Y_c \), and \( Z_c \)-axes, which correspond to right and left, far and close, and up and down motions. The imaginary controlled object moves in the \( X_r \)-axis direction in motion 1. In the experimental results in Fig. 5(a), the wrist moves in the \( X_a \)-axis direction macroscopically, and it makes a parallel motion in the right and left directions to match the imaginary controlled object. However, in detail, the wrist makes a curve that is slightly convex to the \( Y_a \)-axis positive side in the \( X_aY_a \) plane. The imaginary controlled object moves in the \( Y_c \)-axis direction in motion 2, and the wrist also moves in the \( Y_a \)-axis direction macroscopically, as shown in Fig. 5(a). However, the path of the wrist inclines slightly against the \( Y_a \)-axis direction. In motion 3, the imaginary controlled object moves in the \( Z_c \)-axis direction, and the wrist also moves approximately in the \( Z_a \)-axis direction in the experiment. However, the wrist makes a slightly convex curve to the \( Y_a \)-axis positive side in the \( Y_aZ_a \) plane.

Figure 5(b) shows the results for motions 14, 15, 16, and 17 in which the motion of the imaginary controlled object is parallel to motion 1 (right and left directional motion). All results are approximately parallel to the \( X_a \)-axis. The paths
Motion 1  Motion 2  Motion 3
(a) Basic motions in right and left, far and close, and up and down directions

Motion 14  Motion 15  Motion 16  Motion 17
(b) Motions parallel to motion 1 (motions in right and left directions)

Motion 18  Motion 19  Motion 20  Motion 21
(c) Motions parallel to motion 2 (motions in far and close directions)

Motion 22  Motion 23  Motion 24  Motion 25
(d) Motions parallel to motion 3 (motions in up and down directions)
tend to become a curve that is slightly convex to the \( Y_w \)-axis positive side, but the degree of curvature differs. Thus, the same tendency seen in motion 1 is observed in these motions. Figure 5(c) shows the results for motions 18, 19, 20, and 21, in which the motion of the imaginary controlled object is parallel to motion 2 (forward and backward directional motion). Although all results are in the \( Y_w \)-axis direction, the path inclines against the \( Y_w \)-axis for motions 18 and 19. Figure 5(d) shows the results for motions 22, 23, 24, and 25, in which the motion of the imaginary controlled object is parallel to motion 3 (far and close directional motion). All results are approximately parallel to the \( Z_w \)-axis; however, the paths tend to become curves that are slightly convex to the \( Y_w \)-axis positive side. Thus, the same tendency found in motion 3 is observed in these motions.

The result that the path of the wrist is not linear but curved is next discussed. All experimental results for all participants were investigated. For motions 1, 14, 15, 16, and 17, in which the imaginary controlled object moves parallel to the \( X_w \)-axis, the paths tended to become curves that are slightly convex to the \( Y_w \)-axis positive side in 84% of the experiments, as judged by visual observation. For motions 3, 22, 23, 24, and 25, in which the imaginary controlled object moves parallel to the \( Z_w \)-axis, the paths tended to become curves that are slightly convex to the \( Y_w \)-axis positive side in 80% of the experiments, as again judged by visual observation.

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Fig. 5  Paths of wrist joint center of a participant (unit: mm)
Next, the results in the case that the imaginary controlled object performs biaxial diagonal movement among the three axial directions $X_o$, $Y_o$, and $Z_o$ (motions 4, 5, 6, 7, 8, and 9) are shown in Fig. 5(e). All cases have approximately the same motion as that of the imaginary controlled object. However, for motions 4, 5, 8, and 9 in which the motion of the imaginary controlled object includes a moving component in the $X_o$-axis direction, the paths become convex to the $Y_o$-axis positive side in the $X_oY_o$ plane. For motions 6, 8, and 9, in which the motion of the imaginary controlled object includes the moving component in the $Z_o$-axis direction, the paths become convex to the $Y_o$-axis positive side in the $Y_oZ_o$ plane, but the degree of curvature differs.

Finally, the results for the case where the imaginary controlled object performs three-axial $X_oY_oZ_o$ diagonal movement (motions 10, 11, 12, and 13) are shown in Fig. 5(f). Although all cases have approximately the same motion as that of the imaginary controlled object, the paths tend to become convex to the $Y_o$-axis positive side.

2.4 Discussion on Experiment

The participants were given a survey after the experiment. All participants commented that they intended to move their wrist joint center in the same motion as the imaginary controlled object. Actually, the participants moved their wrist joint center in curves, although they intended to move them linearly. Therefore, it is revealed that a difference exists between the intended arm motion and the actual motion, and curved motion tends to be made even if a linear motion is intended. If it is assumed that an object such as a robot is controlled by the motion of the arm, the result obtained here indicates that the controlled object performs a slightly different motion than the intended arm motion of the operator if the command to the controlled object is made to move in exactly the same way as the arm motion of the operator.

The experimental results also revealed that when the imaginary controlled object moves in the $X_o$-axis direction, the actual wrist motion of the participant is mainly an $X_o$-axis directional motion; however, the path becomes convex to the $Y_o$-axis positive side. This characteristic appears not only in the case that the wrist moves near the center of the motion area of the imaginary controlled object (motion 1) but also in the case that the wrist moves in other positions (motions 14, 15, 16, and 17). Thus, this characteristic is likely to appear regardless of the position. In addition, not only in the case that the imaginary controlled object moves simply in the $X_o$-axis direction but also in the case that it moves in the diagonal direction including the $X_o$-axis direction, the path of the actual motion of the wrist tends to become convex to the $Y_o$-axis positive side in the $X_oY_o$ plane. In other words, the path of the actual motion of the wrist becomes convex to the $Y_o$-axis positive side when the motion of the imaginary controlled object includes the $X_o$-axis direction component.

Similarly, when the imaginary controlled object moves in the $Z_o$-axis direction, the wrist of the participant moves mainly in the $Z_o$-axis direction; however, the path becomes convex to the $Y_o$-axis positive side. This characteristic appears at various positions in the motion area of the imaginary controlled object (motions 3, 22, 23, 24, and 25). In addition, even in the case that the imaginary controlled object moves in a diagonal direction that includes the $Z_o$-axis direction, the path of the actual motion of the wrist tends to become convex to the $Y_o$-axis positive side in the $Y_oZ_o$ plane. In other words, the path of the actual motion of the wrist becomes convex to the $Y_o$-axis positive side when the motion of the imaginary controlled object includes the $Z_o$-axis direction component.

Suppose that the command to the controlled object is made to move exactly the same as the arm motion of the operator. Then if an $X_o$-axis or $Z_o$-axis directional motion component is included in the intended motion of the operator, the motion of the controlled object becomes slightly convex to the $Y_o$-axis positive side in comparison with the intended motion of the operator.

3. Proposal of conversion equations to generate position command considering motion characteristic of human arm

In the previous section, it was revealed that the intended arm motion and the actual motion are different, and curved motion tends to be made even when linear motion is intended. In this section, the result of the arm motion experiment carried out in the previous section is analyzed. Based on the analysis result, equations to convert the arm motion data into the motion command of the controlled object are constructed.

In the conventional method, the controlled object moves with the exact same motion as arm motion of the operator.
The wrist joint center and the controlled object make the same motion. This correspondence is carried out by a simple conversion equation. The simple conversion equation is expressed as follows, where the position of the imaginary controlled object in the coordinate system for motion of the imaginary controlled object is \((X_o, Y_o, Z_o)\) and the position of the wrist joint center of the operator in the wrist motion coordinate system is \((X_w, Y_w, Z_w)\). The wrist motion area of the operator is within the range of a cube that is 300 mm on each side (Fig. 1(b)), and the motion area of the imaginary controlled object is a cube that is \(l\) (mm) on each side. The difference of their sizes is considered.

\[
\begin{align*}
X_o &= \frac{l}{300}X_w \\
Y_o &= \frac{l}{300}Y_w \\
Z_o &= \frac{l}{300}Z_w
\end{align*}
\]  

(1)

In contrast, in the novel operating method in this study, the convex curve of the path of the wrist joint center is expressed by a quadratic function in the wrist motion coordinate system. The convex curve of the path of the wrist joint center is often convex to the \(Y_w\)-axis positive side in the \(X_wY_w\) plane or the \(Y_wZ_w\) plane when the operator intends to move his/her wrist joint center linearly toward the \(X_w\)-axis direction or the \(Z_w\)-axis direction. As the experimental result of motion 1 shown in Fig. 5(a), the path becomes a curve convex to the \(Y_w\)-axis positive side in the \(X_wY_w\) plane when the wrist joint center makes the \(X_w\)-axis directional motion. In such a case, the participant did not intend to move his/her wrist joint center in the \(Y_w\)-axis direction. Thus, the displacement in the \(Y_w\)-axis direction in the experimental result of motion 1 shown in Fig. 5(a) was unintended, and it is concluded that a function \(f(X_w)\) decreasing in proportion to the square of \(X_w\) is included in the value of \(Y_w\). Similarly, the path becomes a curve convex to the \(Y_w\)-axis positive side in the \(Y_wZ_w\) plane when the wrist joint center makes the \(Z_w\)-axis directional motion, as shown in Fig. 5(a). It can be concluded that a function \(f(Z_w)\) decreasing in proportion to the square of \(Z_w\) is included in the value of \(Y_w\). Therefore, a method to generate an operation command modifying the convex trend was devised in this study.

First, the conversion equation to modify the displacement of \(X_w\)-axis directional motion is presented. A term is added in conversion equation (1) to modify the characteristic that a function \(f(X_w)\) decreasing in proportion to the square of \(X_w\) is included in the value of \(Y_w\). Thus, the conversion equation from input \((X_w, Y_w, Z_w)\) to operation command \((X_o, Y_o, Z_o)\) is expressed as follows by using a constant \(a_1\).

\[
\begin{align*}
X_o &= \frac{l}{300}X_w \\
Y_o &= \frac{l}{300}(Y_w + a_1X_w^2) \\
Z_o &= \frac{l}{300}Z_w \\
a_1 &= 8.32 \times 10^{-4}
\end{align*}
\]  

(2)

Similarly, the conversion equation to modify the displacement of \(Z_w\)-axis directional motion is constructed by using a constant \(a_2\).

\[
\begin{align*}
X_o &= \frac{l}{300}X_w \\
Y_o &= \frac{l}{300}(Y_w + a_2Z_w^2) \\
Z_o &= \frac{l}{300}Z_w \\
a_2 &= 8.06 \times 10^{-4}
\end{align*}
\]  

(3)

The constants \(a_1\) and \(a_2\) determine the curvature of the actual path of the arm when the operator intended to move his/her wrist joint center toward the \(X_w\)-axis direction or the \(Z_w\)-axis direction linearly. The values are selected so that they represent the curvature, which is based on the observation of the curvature of the path in motion 1, motion 3, and other motions in the experimental results. The authors compared the paths in the experimental result with quadratic
curves by visual observation and determined the values. The least squares method was not used. When the operation command is modified by these equations, it is thought that the intended positioning operation considering the motion characteristic of the human arm is realized.

In addition, the conversion equation modifying the displacement of both the $X_w$- and $Z_w$-axis directional motions is obtained by combining conversion equations (2) and (3). The conversion equation is expressed as follows.

$$\begin{align*}
X_w &= \frac{l}{300} X_w \\
Y_w &= \frac{l}{300} \left( Y_w + 8.32 \times 10^4 X_w^2 + 8.06 \times 10^4 Z_w^2 \right) \\
Z_w &= \frac{1}{300} Z_w
\end{align*}$$

(4)

To illustrate the use of conversion equation (2), Fig. 6 shows the points that correspond to $X_w$ and $Y_w$ shown on the $X_wY_w$ plane when $X_0$ is changed under the conditions $l = 300$ mm, $Y_w = 0$, and $Z_w = 0$. This curve corresponds to the actual path of the wrist when the operator intends to move his/her arm linearly in the $X_w$-axis direction. It is verified that the conversion equation can express a curved form similar to the experimental result obtained in section 2. If conversion equation (2) is used in the case that the actual wrist motion follows this curve, then the output operation command is a linear motion command such that $Y_w$ is always zero and only $X_w$ is changed. In the same way, by using conversion equation (3), Fig. 7 shows the points that correspond to $Y_w$ and $Z_w$ shown on the $Y_wZ_w$ plane when $Z_0$ is changed under the conditions $l = 300$ mm, $X_w = 0$, and $Y_w = 0$. This curve corresponds to the actual path of the wrist when the operator intends to move his/her arm straight in the $Z_w$-axis direction. This method can express the same curve as the experimental result observed in section 2. If conversion equation (3) is used in the case that the actual path of the wrist is this curve, then the output operation command is a linear motion command such that $Y_w$ is always zero and only $Z_w$ is changed. The conversion equations which modify three kinds of motion (motion in the $X_w$-axis direction, motion in the $Z_w$-axis direction, and motion in both the $X_w$- and the $Z_w$-axis directions) are constructed.

**Fig. 6** $X_w$ and $Y_w$ in conversion equation (2), where $X_0$ is changed under $l = 300$ mm, $Y_w = 0$, $Z_w = 0$

**Fig. 7** $Y_w$ and $Z_w$ in conversion equation (3), where $Z_0$ is changed under $l = 300$ mm, $X_w = 0$, $Y_w = 0$

### 4. Evaluation experiment of effectiveness of proposed operating method

Next, an evaluation experiment was conducted to verify the effectiveness when the operation is performed by the novel proposed conversion equations (Eqs. (2), (3), and (4)), which consider the motion characteristics of the human arm. In addition, the simple conventional conversion equation (Eq. (1)) was evaluated in the experiment. The experimental results of the proposed conversion equations are compared to the simple conventional equation.
4.1 Method of evaluation experiment
4.1.1 Device for evaluation experiment

This section describes the experiment in which the operator operates the imaginary controlled object on the screen by the motion of his/her arm. Although the outline of the experimental device is similar to that of the experiment in section 2 (see Fig. 2), the operator can operate the imaginary controlled object on the screen by the motion of his/her arm (the change of the position of the wrist joint center). The imaginary controlled object is displayed in the virtual space on the screen. The position of the wrist joint center is calculated by measurement using real-time motion capture, and the imaginary controlled object is moved to the position corresponding to the position of the wrist joint center in the virtual space. In this way, the operator is able to operate the imaginary controlled object by his/her arm.

4.1.2 Game in evaluation experiment

The operation method is evaluated in a game in which the position of the imaginary controlled object is moved. In the game, a target appears at a random position in the virtual space, and the operator moves the position of the imaginary controlled object to that of the target. As shown in Fig. 8(a), three circles are displayed: the blue circle is the imaginary controlled object, the red circle is the target, and the pink circle is the previous target. When the imaginary controlled object reaches the target position as shown in Fig. 8(b), the next target appears and the previous target changes to pink at the same time, as shown in Fig. 8(c), and the target route connecting the previous target and the next target appears. Then, as shown in Fig. 8(d), the operator moves the imaginary controlled object toward the next target. Note that the target route connecting the previous target and the next target is along circumscribing lines of the previous target circle and the next target circle. A fixed number of targets appear in one game, and the game ends when the imaginary controlled object reaches the last target. The goal of the operator is to finish the game as quickly as possible and to move the imaginary controlled object along the displayed target route as accurately as possible.

![Fig. 8 Schematic images of imaginary controlled object, previous target, next target, and target route on screen](image)

The operability is evaluated by the required time to reach the target position and the tracing accuracy on the target route. The required time is evaluated as the time required to finish a game. The tracing accuracy on the target route is evaluated based on the time average of the length of the perpendicular line from the position of the imaginary controlled object to the center line of the target route (the line connecting the center of the next target circle and that of the previous target circle). In this case, the smaller the time average of the length of the perpendicular line is, the higher the tracing accuracy is.

In this experiment, the number of targets appearing in one game is seven. Three kinds of appearance patterns in which the target appears at random positions (3D-path) are given so that the appearance position is not biased. In addition, to evaluate the conversion equation for modifying the displacement of $X_c$-axis directional motion and that of $Z_w$-axis directional motion, five kinds of appearance patterns in which the target appears only on the $X_c$-axis ($X$-path) and five kinds of appearance patterns in which the target appears only on the $Z_w$-axis ($Z$-path) are given. One set consists of 26 games in which these 13 kinds of appearance patterns appear two times.

In this experiment, when the relation between the position of the imaginary controlled object ($X_c$, $Y_c$, $Z_w$) and that of
the target \((X, Y, Z)\) satisfies the following condition for one second continuously, it is judged that the imaginary controlled object has reached the target position. Here, \(l\) is the length of one side of the cube of the virtual space on the screen.

\[
\begin{align*}
|X_o - X| &\leq \frac{l}{30} \\
|Y_o - Y| &\leq \frac{l}{30} \\
|Z_o - Z| &\leq \frac{l}{30}
\end{align*}
\] (5)

This condition is set to avoid recognizing the condition that the position of the imaginary controlled object is unintentionally on the target position as that of the imaginary controlled object has intentionally reached the target position. In addition, to make it easy for the participant to recognize that the position of the imaginary controlled object has reached the target position visually, as shown in Fig. 9, the blue circle displaying the position of the imaginary controlled object changes to red, which is same color as the target circle when the imaginary controlled object has reached the target position (the condition of Eq. (5) is satisfied).

The process of the game is as follows.

1. First, a target (start target) appears at the position \((X_o, Y_o, Z_o) = (0, 0, 0)\) in the virtual space. The participant operates the imaginary controlled object, and when the imaginary controlled object reaches the position of the starting target, the measurement of the time for the game starts. At the same time, the first target and the target route appear, and the start target is displayed in pink.

2. The participant moves the imaginary controlled object so that it follows the target route as much as possible. When the imaginary controlled object reaches the first target, the second target and the next target route appear, and the first target is displayed in pink. Then, the new target and the target route appear successively in the same way.

3. When the imaginary controlled object reaches the seventh target, the game ends and the measurement of the time required for the game is complete.

4. The result is evaluated according to the required time for the game and the tracing accuracy on the target route.

![Figure 9 Schematic image of changes in display when imaginary controlled object reaches target](image)

(a) State in which imaginary controlled object is not on target  
(b) State in which imaginary controlled object is on target

4.1.3 Procedure of experiment

The participants are six physically unimpaired adults. A participant moves the position of the imaginary controlled object in the virtual space on the screen and plays the game. The four conversion equations are used and compared; these are the simple type expressed by Eq. (1) and the novel proposed types expressed by Eqs. (2), (3), and (4). For each conversion equation, one set of 26 games are played.

It is desirable for the participant to be experienced with the display of the virtual space before the games. Therefore, a practice task for each participant to get used to the display is prepared before the experiment. In the task, the participant grasps the marker for the motion capture by hand and moves it, and is allowed to freely operate the imaginary controlled object until he/she gets accustomed to the display.

The series of experiments is carried out for one participant over eight days. Table 1 shows the schedule of the
experiment. The participant plays only one set of games a day, and an interval of one day or more separates each experiment. The reason for this is that the participant should forget the sense of operation given by using a previous conversion equation. In the early state, the participant is less used to the experiment, but as the experience with the experiment increases, it is supposed that the participant becomes used to the operation of the imaginary controlled object on the screen and becomes able to operate with high accuracy in less time. Therefore, the experiment is carried out along the schedule in Table 1. The experiment from day 1 to day 4 is treated as the pre-experiment for practice, and the data from day 5 to day 8 are treated as the main experimental data.

| Table 1 | Schedule for experiment |
|---------|-------------------------|
|         | Day 1 | Day 2 | Day 3 | Day 4 | Day 5 | Day 6 | Day 7 | Day 8 |
| Applied conversion equation | (1)   | (2)   | (3)   | (4)   | (3)   | (2)   | (1)   |

The game method was explained to the participants. At the same time, the participants were told that the score was evaluated as the required time for one game and the tracing accuracy on the target route. The participants were instructed to operate the imaginary controlled object as quickly and as accurately as possible. On the other hand, information about the conversion equations was not given to the participants.

4.2 Experimental results

Figure 10 shows the results obtained in this experiment. The means and the confidence intervals of all participants are shown. For the tracing accuracy on the target route, the calculation is performed by assuming that the length of one side of the cube in the virtual space is 300 mm, which is the same length as one side of the wrist motion area, so that the shown result can be easily understood.

![Graph showing the results of experimental evaluation of operability (means and confidence intervals of all participants)](image)

First, the results of conversion equation (2) modifying the displacement of $X_w$-axis directional motion and simple conversion equation (1) are compared. The required time by conversion equation (2) is reduced by approximately 9% on 3D-path, approximately 12% on $X$-path, and approximately 8% on $Z$-path. For $X$-path and $Z$-path, the difference is statistically significant at a level of 5%. For the tracing accuracy on the target route, the accuracy by conversion equation (2) is higher by approximately 18% in $X$-path and approximately the same level on 3D-path and $Z$-path. The difference for $X$-path is statistically significant. Thus, conversion equation (2) modifying the displacement of $X_w$-axis directional motion is effective. The result specifically shows high effectiveness of motion only in the $X_w$-axis direction.

Second, the results of conversion equation (3) modifying the displacement of $Z_w$-axis directional motion and simple conversion equation (1) are compared. The required time by conversion equation (3) is reduced by approximately 9% on 3D-path, approximately 6% on $X$-path, and approximately 12% on $Z$-path. For $X$-path and $Z$-path, the difference is statistically significant at a level of 5%. For the tracing accuracy on the target route, the accuracy by conversion equation (3) is higher by approximately 16% on $Z$-path and is approximately the same level on 3D-path and $X$-path.
The difference for Z-path is statistically significant. Thus, conversion equation (3) modifying the displacement of \(Z_w\)-axis directional motion is effective. The result specifically shows high effectiveness of motion only in the \(Z_w\)-axis direction.

Finally, the results of conversion equation (4) modifying the displacement of both \(X_w\) and \(Z_w\)-axis directional motion and simple conversion equation (1) are compared. The required time by conversion equation (4) is reduced by approximately 8% on X-path and approximately 5% on Z-path. On 3D-path, conversion equation (4) and simple conversion equation (1) are at the same level. For the tracing accuracy on the target route, the result by simple conversion equation (4) is improved by 15% on X-path and at the same level on Z-path, but it is deteriorated by 8% on 3D-path. Thus, it is supposed that conversion equation (4) modifying the displacement of both \(X_w\) and \(Z_w\)-axis directional motion is less effective than those of \(X_w\)-axis directional motion only by conversion equation (2) and \(Z_w\)-axis directional motion only by conversion equation (3).

The results of the required time are summarized. \(X_w\)-modification conversion equation (2) is effective on X-path with a statistically significant difference, and it seems to be slightly effective on 3D-path. \(Z_w\)-modification conversion equation (3) is effective on Z-path with a statistically significant difference, and it seems to be slightly effective on 3D-path. \(X_wZ_w\)-modification conversion equation (4) is effective on X-path with a statistically significant difference, slightly effective on Z-path, and at the same level on 3D-path. The effectiveness of \(X_wZ_w\)-modification conversion equation (4) is lower than that of \(X_w\)-modification conversion equation (2) and \(Z_w\)-modification conversion equation (3). For X-path, the three proposed conversion equations show a better result than simple conversion equation (1), and the best result is shown by conversion equation (2) modifying the displacement of \(X_w\)-axis directional motion. For Z-path, the three proposed conversion equations show better results than simple conversion equation (1), and the best result is shown by conversion equation (3) modifying the displacement of \(Z_w\)-axis directional motion. For the 3D-path, the effectiveness of the proposed conversion equations is lower than that for X-path and Z-path.

Next, the result concerning the tracing accuracy is summarized. \(X_w\)-modification conversion equation (2) is effective on X-path with a statistically significant difference, and it is at the same level on 3D-path. \(Z_w\)-modification conversion equation (3) is effective on Z-path with a statistically significant difference, and it is at the same level on 3D-path. \(X_wZ_w\)-modification conversion equation (4) is effective on X-path with a statistically significant difference, and it is at the same level on Z-path but deteriorates on 3D-path. The effectiveness of \(X_wZ_w\)-modification conversion equation (4) is lower than that of \(X_w\)-modification conversion equation (2) and that of \(Z_w\)-modification conversion equation (3). The effectiveness of the proposed conversion equations is lower on 3D-path than on X-path and Z-path.

The effectiveness of the applied conversion equations is compared between the required time and the tracing accuracy. For the required time, the novel proposed conversion equation shows many examples of better results than does the simple conversion equation. However, for the tracing accuracy, the examples of better results decrease. On the other hand, in the examples that show the novel proposed conversion equations having better results than the simple conversion equation, the difference between the proposed conversion equation and the simple conversion equation is large in tracing accuracy, whereas the difference is smaller in required time.

4.3 Discussion on Evaluation Experiment

As shown in section 2, a difference exists between the intended arm motion of a human and the actual arm motion. In the investigation conducted in section 2, the participant moved his/her arm while looking at the motion of the imaginary controlled object, and the participant could not see the motion of his/her own arm. Accordingly, it was impossible to modify the motion by seeing the difference between the intended arm motion and the actual arm motion. In contrast, in the evaluation experiment in section 4, the participant could see the motion of the object operated by his/her arm and could recognize the difference between the intended arm motion and the actual arm motion. Therefore, the participant could modify his/her arm motion if the arm motion was different from the intended motion. It is thought that the simple conversion equation possibly showed better or similar results than the novel proposed conversion equations. However, the novel proposed conversion equations showed better results on the whole. As the results indicate, an effective conversion equation was constructed even in the case that the operator could modify his/her own arm motion by seeing the motion of the controlled object.

In the experiment in section 2, repeated measurements were performed for the same motions (far and close, right and left, up and down, and diagonal directions). On the other hand, in the evaluation experiment in this section, the
position of the target randomly changed and the participant traced it. Even in the case of this difference, it was verified that the proposed method using conversion equations was effective. The experimental results indicate that the conversion equation modifying the displacement of both \( X_w \) - and \( Z_w \) -axis directional motion was less effective than those of \( X_w \) -axis directional motion only and of \( Z_w \) -axis directional motion only. Specifically, the tracing accuracy deteriorated on 3D-path in comparison with that using the simple conversion equation. The position of the wrist joint center sometimes moved to the near end point of the cube of the wrist motion area on 3D-path. In such a case, the value of the modification term in novel proposed conversion equation (4) is large because the absolute values of \( X_w \) and \( Z_w \) are large. An unintended displacement of the position of the wrist joint center arises, but if the unintended displacement becomes larger than a certain level, it is supposed that the participant notices the unintended displacement and modifies the position by himself/herself. In such a case, the effect of the modification term in novel proposed conversion equation (4) becomes too large, and the effectiveness of the conversion equation is decreased. It is thought that this is the reason that the conversion equation modifying displacement of both \( X_w \) - and \( Z_w \) -axis directional motion is less effective than those of \( X_w \) -axis directional motion only and of \( Z_w \) -axis directional motion only.

5. Conclusion

When three-dimensional positioning devices, such as a robot arm, move in space with multiple degrees of freedom, it is desirable that the devices be able to be intuitively operated without prior practice. As one easy operating method, a human operator moves his/her arm and the robot or device is commanded to make the same motion. In this method, the robot traces exactly the same motion as the human arm. However, in the case that the operator moves his arm with an intended specific motion, it is not confirmed whether the actual arm motion agrees with the intended motion, and a difference possibly exists between them. In such a case, the robot performs a different motion from the intended motion of the operator. Therefore, in this study, the accuracy of the motion of the arm of the operator was evaluated by observing the differences between the intended and actual motions. By considering these differences, an operating method using conversion equations to calculate the intended arm motion of the operator was established. An experiment confirmed the effectiveness of the operation by using the proposed operating method. The following results were obtained.

1) Supposing that the participant operates an object by his/her arm motion, the difference between the intended arm motion and the actual arm motion was investigated in an experiment. The results revealed that the participant moved the wrist joint center along a curved path even though the participant intended to move it linearly. It was clarified that this difference exists between the intended arm motion and the actual arm motion, and the actual motion tends to be curved even when linear motion is intended.

2) In the case that the participant intended to move the wrist position linearly in the right and left directions or the up and down directions, the actual wrist position moved in a curve convex to the far direction. This convex shape appeared also in the case that the participant intended to move the wrist position linearly in the diagonal direction, including the right and left directions or up and down directions.

3) Considering the difference between the intended arm motion and actual arm motion, an operating method using conversion equations to calculate the intended arm motion of the operator from the actual arm motion was constructed.

4) An evaluation experiment of the effectiveness of the proposed operating method using conversion equations was carried out. In the experiment, the participant operated the object by arm motion and moved the object along the target route as quickly as possible. The simple conventional conversion equation in which the object is moved exactly the same as the actual arm motion was used for comparison. For the required time, the conversion equation considering the right and left directional motion characteristic was effective in the right and left directional routes, and slightly effective in the three-dimensional route. For the tracing accuracy, the same conversion equation was effective in the right and left directional routes, and equivalent to the simple conversion equation in the three-dimensional route. The conversion equation considering the up and down directional motion characteristic showed similar effectiveness. The results confirmed the effectiveness of the proposed operating method using conversion equations.
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