In recent years, a medical procedure called interventional radiology (IR) has been attracting considerable attention. Doctors can perform IR percutaneously while observing the fluoroscopic image of patients. Therefore, this surgical method is less invasive. In this surgery, computed tomography (CT) equipment is often used for precise fluoroscopy. However, doctors are exposed to strong radiation from the CT equipment. In order to overcome this problem, we have developed a remote-controlled surgical assistance robot called Zerobot. In animal puncture experiment, the operation of Zerobot was based on joint control. Therefore, during a surgery, the tip of the needle moves when a surgeon orders for a change in the direction of the needle. This makes the robot less user-friendly because the surgeon tracks the trajectory of the tip of the needle. This problem can be solved by using remote center control.

Keywords: surgical assistance robot, interventional radiology, puncture robot

1. Introduction

Interventional radiology (IR) is a surgical method conducted with imaging modalities such as computed tomography (CT) and X-rays. A surgeon conducts IR percutaneously by inserting a needle or a catheter into body of a patient while observing medical images of the patient. In particular, the CT equipment has high visibility and objectivity. CT fluoroscopy systems, which can show medical images in real-time, are superior as guiding tools for IR. Therefore, CT-guided IR is used in lung cancer treatment, liver cancer treatment, biopsy, etc. [1]. The manual IR treatment is illustrated in Fig. 1. When compared to the conventional methods, IR can be conducted under local anesthesia and is minimally invasive. Moreover, patients can be discharged from the hospital within three or four days after the treatment. Because of these advantages, IR is paid much attention in recent years. According to clinical data, the minimum size of malignancy is approximately 3 mm in diameter [2]. Therefore, surgeons must puncture such small malignant tumors carefully and accurately by using needles. In addition, surgeons are exposed to radiation during CT scanning because they conduct the procedure close to the CT gantry.

In order to prevent radiation exposure, surgeons wear radiation protection aprons and hold needles using forceps; this creates a distance between the hand and the CT radiography plane. However, it is impossible to prevent radiation exposure completely. Medical robots and IR training systems, such as AcuBot [3], CT-Bot [4], MAXIO [5], and others [6, 7], are developed in order to improve the positioning accuracy of needles and to reduce radiation exposure. These robots assist the surgeons in inserting a needle during a CT-guided puncture. However, Zerobot, which is developed by us, assists the surgeon throughout the process (from positioning the robot
to inserting a needle) by remote control.

In this research, in order to confirm the problems with robotic IR systems, we conducted a phantom puncture experiment [8] and an animal puncture experiment [9]. From these experiments, it was confirmed that adjusting the position of the needle without changing the position of the tip of the needle is troublesome. This is because the tip of the needle moves when a surgeon orders a change in the direction of the needle. In order to solve this problem, remote center control should be adjusted into Zerobot. Remote center control is a method in which some active joints are controlled synchronously in order to set the center of rotation to an arbitrary point. If center of rotation is set as the tip of the needle, the needle posture can be changed without changing the position of the tip of the needle. Thus, in this control method, Zerobot simplifies the procedure of the IR surgery. In AcuBot, remote center control is implemented by using a mechanical structure called MINI-RCM. MINI-RCM adapts to various needles by adjusting an RCM point, which is the needle pivoting point, during the needle orientation. However, during needle insertion, the RCM point cannot be changed actively from the needle entry point because the point is constrained by the mechanical structure, which is manually preset. From our animal experiment, it is confirmed that the needle deflects when inserted into a living body. In that case, surgeons have to orient the posture of the needles frequently for eliminating the deflection of the needles. We assumed that an optimal RCM point for decreasing the deflection of the needle and the body tissue is not only the needle entry point. Therefore, we implemented remote center control by calculating the positions of all the axes synchronously so that the RCM point can be changed actively.

According to the minimum size of malignancy, which is approximately 3 mm in diameter, we set the target positioning accuracy of the tip of the needle as 1.0 mm. Therefore Zerobot must archive the target accuracy if it was controlled by a remote center. Then, we conducted an experiment for evaluating the positioning accuracy of the tip of the needle in remote center control.

Zerobot, procedure of puncture, interface devices, and system structure. The forward and inverse kinematics of remote center control are derived in Section 3. In Section 4, an experiment for evaluating the positioning accuracy of the tip of the needle is explained. Finally, Section 5 concludes the paper.

2. Overview of Robotic IR

2.1. System Structure

This subsection describes the system structure of the robotic IR. The system configuration is illustrated in Fig. 3. Zerobot is connected to a computer, which is connected to an interface device using Ethernet. It communicates with the computer through TCP/IP. After receiving the status of the interface device, the computer instructs Zerobot to actuate the axes. Zerobot communicates the angle and displacement of six joints and the value obtained from the force sensor to the interface device. In the interface device, the process that controls the trajectory of Zerobot and the navigation display are segregated. The program that controls Zerobot receives the status of Zerobot. Then, the shared memory sends the status to the navigation display.

2.2. Mechanism

The appearance of Zerobot is shown in Fig. 4. It has five degrees of freedom (DOFs) for adjusting the position of the tip of the needle and the direction of the needle and
one DOF for varying the puncturing direction. Six actuators are included in the machine: four linear actuators (in the directions of X, Y, Z, and puncturing axes) and two rotational actuators (around the X and Y-axes). Three AC servomotors are used for the actuators corresponding to the X, Y, and Z-axes. Three DC servomotors are used for the actuators corresponding to the puncturing axis and around the X and Y-axes. All the motors have digital encoders. Therefore, Zerobot can perform a puncturing operation by actuating the puncturing axis regardless of the posture of the needle. Four wheels are attached to the bottom of the robot so that it can be moved by humans. During a surgery, the robot is fixed under the surgical bed by locking the wheels. The robot changes the direction of the needle and performs the puncturing operation in the CT gantry with its arm above the patient.

If metal parts are present in the gantry, incorrect images called artifacts will appear on the CT images because of a method that is used to reconstruct the images obtained by the CT equipment. If an artifact appears on the CT image, the internal image of the patient will not be clear, and this will cause inconvenience during the surgery. Therefore, metal parts cannot be used for manufacturing needle grippers. Accordingly, needle grippers are made of engineering plastic, which is a radiolucent material. The motor is used in the end effector for puncturing. In addition, the angle of elevation of the CT equipment can be changed as necessary, as shown in Fig. 5. A motor is required for adjusting the direction of the needle corresponding to the elevation angle of the CT equipment. Nevertheless, artifacts occur. These motors cannot be mounted near the needle gripper. Therefore, the motor used for puncturing and the motor used for changing the direction of the needle are located far from CT radiography plane by using a parallel link mechanism at the end effector, as shown in Fig. 6. The front part of the gripping needle is made of polyacetal. Two force sensors are located on the root of the needle gripper. These sensors can measure the moment around the three axes. Using these devices, the reaction force of the skin is calculated and analyzed.

2.3. Puncturing Procedure

This subsection describes the procedure of the robotic IR as follows.

1. Scanning Whole Abdomen:
   The target position of the tumor is confirmed using the CT image of the patient.

2. Planning:
   The relation between the catheter marker and the position of the tumor is confirmed by using the CT image, and the puncture path is planned. Then, a puncturing point is marked on the surface of the skin with a pen.

3. Adjustment of Needle Tip Position and Direction:
   A needle is brought to the CT radiography plane based on the laser emitted from the CT equipment. The position of the tip of the needle is adjusted to the marked position on the surface of the skin. Then, the direction of the needle is also adjusted to the pre-planned angle.

4. Fine Adjustment of Needle Direction:
   Fine adjustments are made to the direction of the needle to direct the needle to the target tumor under CT guidance. Artifact from the needle can be regarded as an extension line of the needle.

5. Puncturing:
   The needle is punctured into the body. When the depth of the puncture is equal to the preplanned value, the surgeon confirms the relation between the position of the tip of the needle and the center of the tumor by observing CT radiography. Then, either the position of the tip of the needle or the direction of the needle is readjusted as necessary.

Zerobot is used in the above-mentioned sequence. If the robot cannot manipulate the needle accurately, the surgeon has to readjust the posture of the needle based on the real-time CT image. This increases the radiation exposure of the patient. Therefore, the positioning accuracy of the robotic hand should be improved.

2.4. Interface System

The design of the interface device is important for the safe operation because the doctor remotely operates Zerobot. The developed interface device is shown in the left side of Fig. 3. This interface consists of nine push buttons and a joystick. The right half of the input panel, which is further to the right side of the joystick, corresponds to
3. Kinematic Analysis

In order to establish remote center control, it requires the knowledge of the forward kinematics and inverse kinematics, which depends on the structure of the robot. The derivations of the forward and inverse kinematics are explained in this section. Zerobot has six active joints and a semi-fixed joint as shown in Fig. 4. The positive direction of each axis is represented by arrows. The semi-fixed axis is set to $-90^\circ$ or $+90^\circ$ as shown in Fig. 8. The angle (in $^\circ$) or displacement (in mm) of the six active axes is defined as $q = [q_1, q_2, \ldots, q_6]^T$. The notations $q_1, q_2, q_3$ and $q_4$ represent linear axes, and $q_4$ and $q_5$ represent rotational axes. The position of the tip of the needle and the posture of the needle are defined as $^{0}r_E = [x, y, z, \phi_X, \phi_Y]^T$ where $\phi_X$ and $\phi_Y$ are defined as in Fig. 8. $\phi_X$ is the angle of the needle on the CT radiography plane, and $\phi_Y$ is the elevation angle of the plane. Forward kinematics is the projection of a vector from $q$ to $^{0}r_E$, and inverse kinematics is the projection of a vector from $^{0}r_E$ to $q$. Hereafter, $\sin \theta$ is represented as $S_\theta$ and $\cos \theta$ as $C_\theta$. It should be noted that, originally, the elements of $C_\alpha$ are included in all the equations of kinematics ($\alpha_3$ is defined in the following subsection). However, $\alpha_3$ can take only $+90^\circ$ or $-90^\circ$. In this case, the value of $C_\alpha$ must be zero. Therefore, in this study, the elements of $C_\alpha$ are omitted from all the equations of kinematics.

3.1. Forward Kinematics

The forward kinematics of Zerobot are derived by using Denavit-Hartenberg notation (DH notation) [10]. The location of the coordinate systems is shown in Fig. 9. These coordinate systems are located according to DH notation. The DH parameters are listed in Table 1. In the table, the value of $\alpha_3$ depends on the direction of the semi-fixed axis. The required parameters $l_1, l_2$ and $l_3$ are defined in Fig. 9. Therefore, we can calculate $^{0}T_E$, which is a homogeneous transformation matrix from $\Sigma_0$ to $\Sigma_6$. In addition, $^{0}T_E$ is just a translational transformation matrix depending on the needle length, $l_E$. Therefore, $^{0}T_E$ can be calculated as follows.

$$^{0}T_E = \begin{bmatrix} -S_{q_4}S_{q_5}S_{q_6} & C_{q_4}S_{q_5} & S_{q_4}C_{q_5}S_{q_6} & 0 \ C_{q_4}C_{q_5}S_{q_6} & C_{q_4}S_{q_5}S_{q_6} & C_{q_4}C_{q_5}S_{q_6} & 0 \ C_{q_4}C_{q_5} & 0 & S_{q_4}C_{q_5} & 0 \ 0 & 0 & 0 & 1 \ \end{bmatrix}$$ (1)

$$^{0}r_{EX} = l_4 - q_3 + \frac{l_2}{2}S_{q_5}S_{q_6} + q_6S_{q_4}C_{q_6}S_{q_5} + l_ES_{q_5}C_{q_5}S_{q_6}$$

$$^{0}r_{EY} = q_5S_{q_6}S_{q_5} + q_2 - l_1S_{q_5} + l_ES_{q_5}S_{q_6}$$

$$^{0}r_{EZ} = q_1 - l_2C_{q_4} - q_6C_{q_4}C_{q_5} - l_EC_{q_4}C_{q_5}$$
Next, \( \phi_A \) and \( \phi_B \), which correspond to the needle posture, should be calculated. Then, the direction vector of the needle represented in \( \Sigma_0 \) is defined as \( ^0\mathbf{n}_E \). \( ^0\mathbf{n}_E \) is the same as the third column direction vector of the rotation matrix, \( ^0\mathbf{T}_E \). Therefore, \( ^0\mathbf{n}_E \) is represented as follows.

\[
^0\mathbf{n}_E = \begin{bmatrix} S_{\theta_5}C_{\theta_3}S_{\alpha_3} & -S_{\theta_5}S_{\alpha_3} & C_{\theta_5}C_{\alpha_3} \end{bmatrix}^T \quad \ldots \quad (2)
\]

Here, \( ^0\mathbf{n}_E \) can also be represented using the notations \( \phi_A \) and \( \phi_B \) as follows. When we include \( \phi_A \) and \( \phi_B \) to the rotation matrix, which can change direction of \( Z \)-axis of \( \Sigma_0 \) same as that of \( \bar{Z}_E \), the third column direction vector of the rotation matrix is \( ^0\mathbf{n}_E \).

\[
^0\mathbf{n}_E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_{\theta_5}C_{\theta_3}S_{\alpha_3} & -S_{\theta_5}S_{\alpha_3} & C_{\theta_5}C_{\alpha_3} \end{bmatrix} \begin{bmatrix} C_{\phi_A} & 0 & S_{\phi_A} \\ 0 & 1 & 0 \\ -S_{\phi_A} & 0 & C_{\phi_A} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} S_{\alpha_5}S_{\phi_A} \\ S_{\alpha_5}C_{\phi_A} \theta_3 \\ -C_{\alpha_5}C_{\phi_A} \theta_3 \end{bmatrix} \quad \ldots \quad \ldots \quad (3)
\]

By comparing Eqs. (2) and (3), we can calculate \( \phi_A \) and \( \phi_B \) shown in Eqs. (4) and (5).

\[
\phi_B = \tan^{-1} \left( \frac{1}{C_{\theta_5}} \tan \theta_5 \right) \quad \ldots \quad \ldots \quad \ldots \quad (4)
\]

\[
\phi_A = \tan^{-1} \left( C_{\phi_B} \tan \theta_4 \right) \quad \ldots \quad \ldots \quad \ldots \quad (5)
\]

Finally, \( ^0\mathbf{r}_E \) is calculated as follows.

\[
^0\mathbf{r}_E = \begin{bmatrix} l_3 - q_3 + l_2S_{\theta_4}S_{\theta_3} + q_6S_{\theta_4} + l_2S_{\theta_5}C_{\theta_3}S_{\alpha_3} + l_5C_{\theta_4}C_{\theta_3}S_{\alpha_3} + l_2S_{\theta_5}C_{\theta_3}C_{\alpha_3} \\ q_0S_{\theta_2} + q_6 - l_1S_{\theta_6} + l_2S_{\theta_5}S_{\alpha_3} + l_2S_{\theta_5}C_{\theta_3}C_{\alpha_3} + l_1C_{\theta_6} - l_2C_{\theta_5}S_{\theta_3}C_{\alpha_3} \\ q_1 - l_2C_{\theta_5} + q_0C_{\theta_5}C_{\theta_3} - l_1C_{\theta_6} - l_2C_{\theta_5}C_{\theta_3} + l_2S_{\theta_5}C_{\theta_3}C_{\alpha_3} \end{bmatrix} \begin{bmatrix} C_{\phi_B} \tan \theta_4 \\ \tan^{-1} \left( \frac{1}{C_{\theta_5}} \tan \theta_5 \right) \end{bmatrix} \quad \ldots \quad \ldots \quad \ldots \quad (6)
\]

### 3.2. Inverse Kinematics

In this subsection, the procedure for deriving the inverse kinematics is described. The target position of the tip of the needle is defined as \( ^0\mathbf{r}_E = [x^*, y^*, z^*, \phi_A, \phi_B]^T \).

<table>
<thead>
<tr>
<th>Table 1. DH parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i )</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
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<tr>
<td>6</td>
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</tbody>
</table>
The target posture of the robot is defined as $\mathbf{q}^* = [q_1^*, q_2^*, \ldots, q_6^*]^T$. According to Eq. (6), the relationship between $\mathbf{q}^*$ and $0\mathbf{r}_E^*$ is represented as follows.

$$\phi_B^* = \tan^{-1}\left(\frac{1}{C_{q_6}^* \tan \phi_A} \right) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 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4.2. Discussion

In this experiment, the target positioning accuracy of the tip of the needle is achieved. According to Table 2, the $Y$ position decreases gradually with the rotation of the needle. In addition, the $Z$ position varies by approximately 0.8 mm. In order to verify this result, we conducted two preliminary experiments by using the same laser sensor. First, the independent controlling accuracy of each axis was confirmed. After deciding origin point of each axis 25 times respectively, the standard deviation of the position of the tip of the needle was obtained. The standard deviation of the positioning accuracy of each axis is listed in Table 3. Second, the reproducibility of the position of the needle tip after reattaching the needle to the end effector was confirmed. The needle was reattached 10 times, and the 3D position of the tip of the needle was acquired every time the needle is reattached. Then the standard deviation of the position of the needle tip was calculated. The standard deviation of the reattached needle tip position is shown in Table 4. According to the results of the preliminary experiment, it can be concluded that there are other causes for the dispersion of the position of the needle tip during remote center control. Then, we assumed that these variations in the position of the tip of the needle were caused by the mismatch in the center of rotation. From Fig. 13, it can be observed that all the positions of the needle tip exist above the center of rotation. In this case, the trajectory of the position of the needle tip shows an upward convex shape. Therefore, the $Y$ position of the tip of the needle is varied. The position of the tip of the needle increases suddenly between $10^\circ$ and $12^\circ$ with respect to the $Z$ position. This phenomenon implies that a mismatch in the center of rotation existed not only on the puncture axis but also on the axis perpendicular to the direction of the needle. It can be considered that the mismatch in the center of rotation was caused by a distortion in the link, an inclination of the linear axes, or a deflection of the needle. However, according to the result of the experiment, the positioning accuracy of the tip of the needle was equal to the target value of 1.0 mm. We concluded that the accuracy was sufficient for an IR surgery assisted by Zerobot.

Table 2. Results of experiment.

<table>
<thead>
<tr>
<th>Target angle</th>
<th>$Y$ position [mm]</th>
<th>$Z$ position [mm]</th>
<th>Measured angle [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-14.0</td>
<td>0.17</td>
<td>-0.115</td>
<td>-13.84</td>
</tr>
<tr>
<td>-12.0</td>
<td>0.267</td>
<td>-0.187</td>
<td>-11.72</td>
</tr>
<tr>
<td>-10.0</td>
<td>0.201</td>
<td>-0.248</td>
<td>-9.99</td>
</tr>
<tr>
<td>-8.0</td>
<td>0.114</td>
<td>-0.131</td>
<td>-7.88</td>
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<tr>
<td>-6.0</td>
<td>-0.005</td>
<td>-0.254</td>
<td>-5.99</td>
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<td>-4.0</td>
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<td>-0.372</td>
<td>-0.049</td>
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</tr>
<tr>
<td>4.0</td>
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<td>-0.334</td>
<td>4.11</td>
</tr>
<tr>
<td>6.0</td>
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<td>-0.18</td>
<td>6.24</td>
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<tr>
<td>8.0</td>
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<td>-0.238</td>
<td>8.17</td>
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<tr>
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<td>-0.165</td>
<td>10.09</td>
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<tr>
<td>12.0</td>
<td>-0.495</td>
<td>0.45</td>
<td>12.11</td>
</tr>
<tr>
<td>14.0</td>
<td>-0.478</td>
<td>0.36</td>
<td>14.15</td>
</tr>
<tr>
<td>Max</td>
<td>0.267</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>-0.495</td>
<td>-0.334</td>
<td></td>
</tr>
<tr>
<td>Max – Min</td>
<td>0.762</td>
<td>0.784</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Accuracy of each axis of Zerobot.

<table>
<thead>
<tr>
<th>Axis</th>
<th>$q_1$</th>
<th>$q_2$</th>
<th>$q_3$</th>
<th>$q_4$</th>
<th>$q_5$</th>
<th>$q_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>0.035 mm</td>
<td>0.036 mm</td>
<td>0.010 mm</td>
<td>0.011°</td>
<td>0.028°</td>
<td>0.026 mm</td>
</tr>
</tbody>
</table>

Table 4. Reproducibility of reattaching needle.

<table>
<thead>
<tr>
<th>Axis</th>
<th>$X$</th>
<th>$Y$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>0.064 mm</td>
<td>0.082 mm</td>
<td>0.223 mm</td>
</tr>
</tbody>
</table>
5. Conclusion

This paper presents an overview of robotic IR, a proposal for remote center control, and an experiment for evaluating the positioning accuracy of the tip of the needle in remote center control. In the experiment, the control system achieved the target accuracy in positioning the tip of the needle. The derived inverse kinematics were also evaluated. Accordingly, it was confirmed that this control method could be used in actual robotic IR surgeries.

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