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Needle Angle Offset Compensation Based on Volume CT Image for Needle Puncture Robot

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Abstract: A medical procedure called Interventional Radiology (IR) gains a lot of attention. Only a needle is inserted into a body of the patient while a doctor observes fluoroscopic image of the body and the needle. Therefore this surgical method is a low invasiveness method. In this surgery, computed tomography (CT) equipment is used, so the doctor is exposed to strong radiation from CT. Thus, we have developed a remote-controlled surgery support robot called "Zerobot", so as to reduce radiation exposure of doctors. Because Zerobot, which has four passive wheels for translation, is placed in front of CT equipment by humans, accurate perpendicularity cannot be guaranteed. Then, perpendicularity between the needle and CT scan plane is required so as to observe whole configuration of the needle on fluoroscopic CT images. Thus, angle offset of the needle, which is held by end-effector of Zerobot, should be compensated. Currently, angle offsets of the needle are measured with visual comparison of CT image by a medical engineer. It is hard for the medical engineer to measure the critically small angle of the needle on the display. In this paper, a method to measure needle angle is proposed. Finally the effectiveness of proposed methods is confirmed through an experiment.

Keywords: Interventional Radiology, Surgery Support Robot, Angle Accuracy Compensation, Volume CT Image.

1 INTRODUCTION

There is a surgical method called Interventional Radiology (IR). This surgical method is conducted with imaging modality such as CT and X-rays. With observing medical images, the doctor conducts IR treatment percutaneously with inserting a needle or a catheter to the patient body. In particular, CT equipment has high visibility and objectivity. And CT fluoroscopy system, which can show medical images in real time, is superior as guiding tool for IR. So CT- guided IR is applied to lung cancer treatment, biopsy, and so on [1]. The image of manual IR treatment is shown in Fig. 1. As compared with conventional survey, IR can be conducted in local anesthesia and this surgical method is minimally-invasive to patients. Moreover patients can be discharged from the hospital about three or four days after treatment. Because of these advantages, IR is paid much attention in recent years. However, IR has disadvantage too. According to the opinion of a doctor, the minimum size of cancer is 5 [mm]. Therefore a doctor must puncture a needle carefully and accurately. In addition, doctors are exposed to radiation during CT fluoroscopy because doctors conduct procedure close to the CT gantry.

In order to prevent radiation exposure, doctors wear radiation protection aprons and handle a needle using a forceps which is useful to make distance between a hand of the doctor and CT measure plane. However, it is impossible to prevent radiation exposure completely. Then some medical robots are developed in order to improve accuracy of positioning of a needle, and to reduce radiation exposure, such as AcuBot [2], CT-Bot [3] and MAXIO [4]. These robots aim to support doctors to insert a needle as CT-guided puncture. On the other hands Zerobot, which is developed by our research group as shown in Fig. 2, aims to conduct whole process from positioning robot to inserting a needle by remote-control.

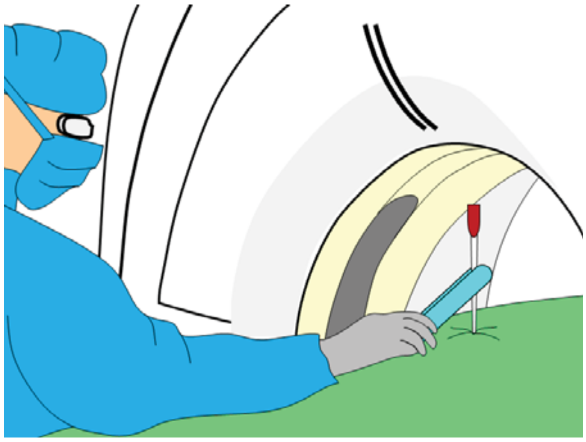

Fig. 1. Manual insertion of a needle in interventional radiology treatment.

In this research, in order to seek the problem of Robotic IR system, we have conducted phantom puncture experiment [5] and animal puncture experiment [6]. In addition, risk management is conducted. We propose a needle angle offset correction method based on principal component analysis based on CT apparatus. Before using Zerobot, we set home position of each axis of Zerobot. After needle angles on each plane is set as zero, volume CT image both of needle and robot are taken. It is checked whether the captured needle is parallel with respect to the CT image section, and is perpendicular to horizontal line on CT image.

If not, the needle angle is measured with observing the CT image by a doctor or a CT technician so as to correct the needle angle offset. Especially when the needle is not parallel with respect to the CT image section, it become impossible to confirm the whole appearance of the needle with a single CT image during the procedure. It brings difficulty the doctor to operate needle through Zerobot. Therefore it is necessary to accurately correct the needle angle offset on CT image.

However, the needle angle offset is very small, and to measure small angle offset on CT image, which is displayed on LCD display, is a heavy burden to the operator. In this paper, we propose a needle angle offset correction method based on principal component analysis based on CT images and confirm the effectiveness by experiment.

2 OVERVIEW OF ZEROBOT

Zerobot in Fig. 2 has six degrees of freedom (DOF) in order to locate an end effector in any position and orientation. In the case of robotic IR system, one degree of freedom is able to be omitted because a degree of freedom around an axis of a needle is not required. Therefore the robot has to have five DOF at least. In addition, according to a procedure of IR, a needle moves almost straight after determining the initial pose of insertion. It is desirable to achieve straight motion by using only one actuator when the robot achieves puncturing motion in order to realize high accuracy.

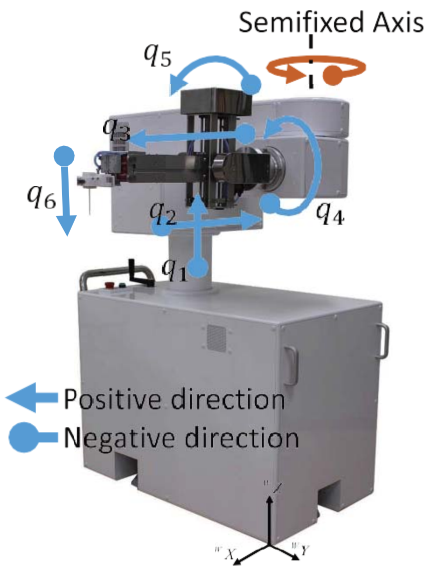

Fig. 2. Appearance of Zerobot.

Artifacts are also an issue to realize a CT-guided puncturing robot. Artifacts are kinds of noise which appear on CT images with black or white shadow. The noise is caused metal materials in a gantry of CT equipment because metal parts absorbs X-ray. Generally, this kind of artifacts tend to occur in the case that X-ray absorption rate of material is high and the X-ray transmittance distance is significantly different according to measuring direction. In addition CT apparatuses for IR has function to incline their gantry. Zerobot has six DOF, so it can fit the held needle onto inclined gantry plane as shown in Fig. 3. ϕ_A and ϕ_B are angles expressing inclination of needle in CT radiography plane and tilt angle of gantry.

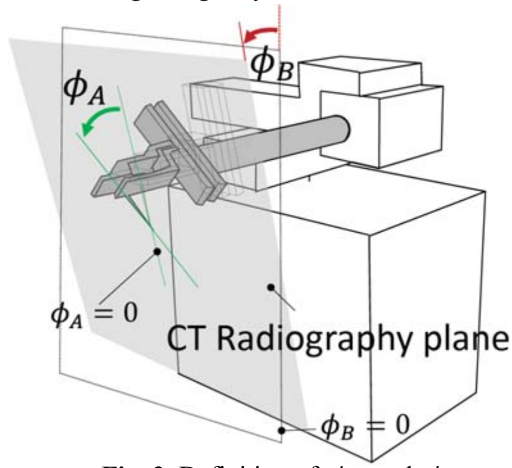

Fig. 3. Definition of ϕ_A and ϕ_B

3 NEEDLE ANGLE CORRECTION WITH PRINCIPAL COMPONENT ANALYSIS

3.1 Methodology

Fig. 4 shows a flowchart of the posture estimation algorithm. First, a composed image is generated from the volume CT data. Next, an area including the needle is found by template matching. Since there are several kinds of needle lengths in commercial lineup, the upper end and lower ends of space including needle are founded. At this time, template matching is conducted based on the assumption that the needle keeps a roughly vertical posture. Finally, the center of gravity and the covariance matrix of the CT image including the needle are calculated, and the inclination of the needle in two dimensional space is obtained from them. The inclination is calculated for the transverse plane and for the sagittal plane from the volume CT data, and those are used for correction of ϕ_A and ϕ_B respectively.

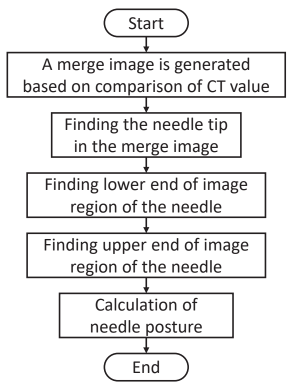

Fig. 4. Flowchart to calculate needle posture

3.2 Image composition of volume CT images

As shown in Fig. 5, the composite image is generated by comparing the CT values of the volume image. The "CT value" means the value of the image data recorded in a DICOM file. A common grayscale image has 256 gray scales. On the other hands, the CT value reconstructed from the radiotransparency is a signed 16-bit grayscale or a 15-bit grayscale. The CT value of the CT image used in this experiment is signed 16 bit gradation. This property is described in each DICOM data. At the moment of image interpretation, the doctor converts this CT value into 256 gradations by using two parameters window center and window width, and confirms the presence or absence of tumors on LCD display screen. The number of CT image pixels is 512 x 512. The coordinate system Σ_I in this paper is defined as shown in Fig. 5.

An image in which the CT value is the largest among the points located at the same pixel position in each CT image is generated as a merge image. Since the CT value of the puncture needle, which is made with a metal, is large, the needle image appears on the merge image. A merge image for volume CT image, which is shown Fig. 6 and includes needle and phantom, is generated as shown in Fig. 7. Since the image of a thin linear object like a needle has less occlusion, the proposed image generation method is suitable to find the appearance of needle.

Next, an image area including the puncture needle is selected by template matching method. Fig. 8 (a) shows a template image used for searching the tip of the needle. The criterion of CT value gives zero value for the substance with the radiation absorptivity equivalent to water, so the space without any objects has a negative value, and metal objects take a large positive value. Therefore, the template image consists of values of ± 1. Although the diameter of the needle is about 1.2 mm, the image blurs due to artifacts. The needle appears with the thickness of 5 mm on the image, so it is necessary to change templates. Fig. 9 shows a map of the evaluation value by the template with respect to the merge image in Fig. 7, wherein the horizontal axis represents the X_I coordinate, and the longitudinal axis represents the Y_I coordinate, and the vertical axis represents the evaluation value. The evaluation values less than -10,000 are not plotted. As shown in Fig. 9, there is a peak near the tip of the needle.

Next proposed method searches the lower end to determine the area that the needle is containing. Fig. 8 (b) shows a template for searching the lower end. In this search, the search is conducted along with only the positive direction of Y_I, which means image lower side. The position where the evaluation value became less than zero was set as the lower end. The template in Fig. 8 (b) coincides with a part of the needle. The condition is selected in the searching for the lower end, in order to find the part where the needle is missing. Fig. 10 shows the transition of the evaluation value with respect to movement to downside. It can be seen that the evaluation value achieves to zero from positive side. Finally searching for the top of the area containing the needle is conducted. Fig. 8(c) shows a template for top edge search. The search is conducted along with only negative direction of Y_I, which means image upper side. The position at which the evaluation value becomes larger than 0 is defined as the upper end. The template in Fig. 8 (c) is for matching with the plastic object grasping the needle. In searching for the top edge, the condition for the evaluation value is set, in order to find the plastic part. Fig. 11 shows the transition of the evaluation value with respect to the movement to upper side. It can be seen that the evaluation value exceeds zero from negative side. Fig. 7 shows the extracted region to calculate the inclination. The horizontal width is set with fixed value, and future improvement is required.

Similarly, the image generation and the template matching method are performed for images in the sagittal plane. The result is shown in Fig. 12.

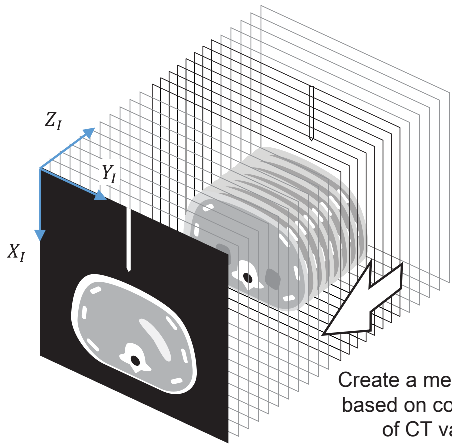

Fig. 5. Merge image generation.

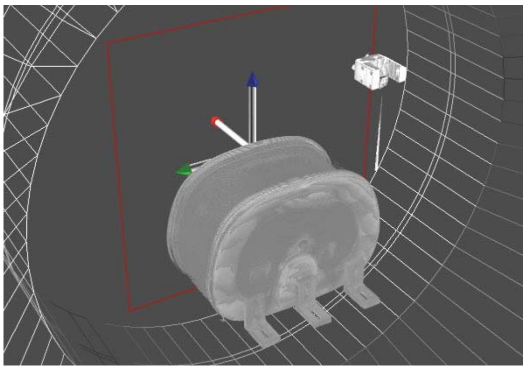

Fig. 6. Volume CT image including both of a phantom and a needle

Fig. 7. Result of extraction of area including needle in transverse plane: Red square indicates region including a needle that is determined by template matching.

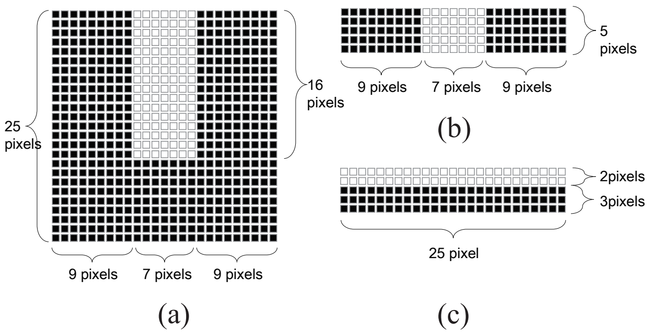

Fig. 8. Template data used for searching the needle tip: Here, the black squares indicate the value of -1, and the white squares indicate the value of +1. (a) is a template used for searching the center of the needle tip, (b) is a template used for searching the lower end of the needle, and (c) is a template used for searching the top of the needle.

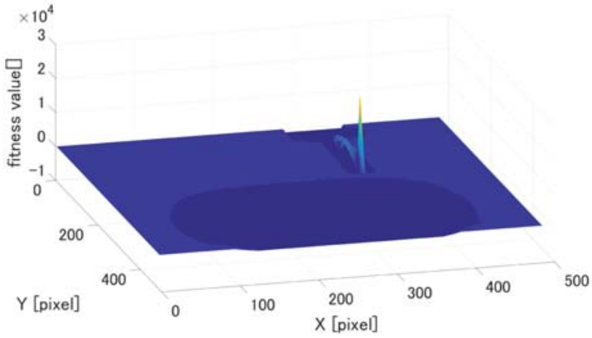

Fig. 9. Fitness map of template matching at the moment to find needle tip.

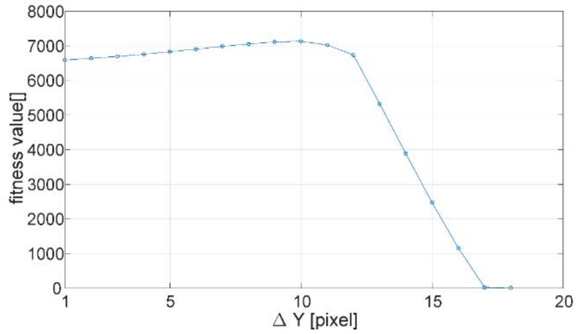

Fig. 10. Fitness value to find lower end of the region.

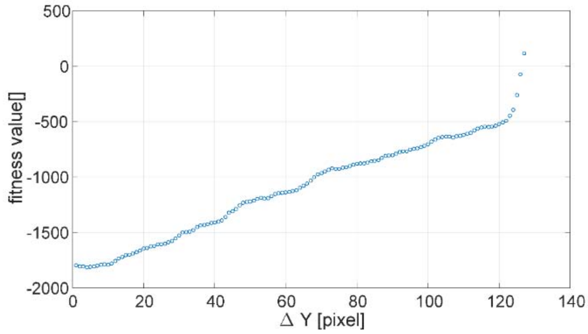

Fig. 11. Fitness value to find upper end of the region.

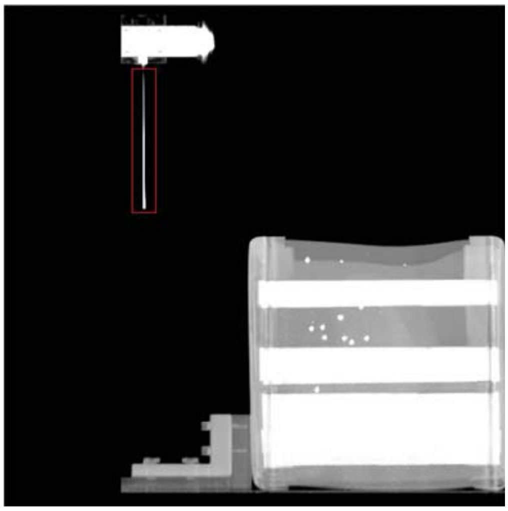

Fig. 12. Result of extraction of area including needle in sagittal plane: Red square indicates region including a needle that is determined by template matching.

3.3 Posture calculation by principal component analysis

Principal component analysis of the CT value is conducted for the extracted region of the obtained merge image so as to calculate the inclination of the needle. First, in principal component analysis, the center of gravity of the needle in the region is calculated using equations (1) and (2).

$$\boldsymbol{x_g} = \frac{\sum_{x,y} \boldsymbol{x}\, \boldsymbol{v}_{(x,y)}}{\sum_{x,y} \boldsymbol{v}_{(x,y)}}, \tag{1}$$

$$y_g = \frac{\sum_{x,y} y\, v_{(x,y)}}{\sum_{x,y} v_{(x,y)}}, \tag{2}$$

here, x_g and y_g mean center of gravity, and $v_{(x,y)}$ is CT value of pixel at $({}^{I}x,\ {}^{I}y)$. Next the covariance matrix σ of the CT value within the needle region is calculated with Eq.(3),

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{xy} & \sigma_{yy} \end{bmatrix}. \tag{3}$$

σ is consist of covariance in x direction σ_{xx}, that in y direction, and covariance between x and y direction σ_{xy}. Those are described as follows.

$$\sigma_{xx} = \frac{\sum_{x,y}(x - x_g)^2 v_{(x,y)}}{\sum_{x,y} v_{(x,y)}}, \tag{4}$$

$$\sigma_{xy} = \frac{\sum_{x,y}(x - x_g)(y - y_g) v_{(x,y)}}{\sum_{x,y} v_{(x,y)}}, \tag{5}$$

$$\sigma_{yy} = \frac{\sum_{x,y}(y - y_g)^2 v_{(x,y)}}{\sum_{x,y} v_{(x,y)}}. \tag{6}$$

The inclination can be calculated with eigenvalues and eigenvectors of the obtained covariance matrix. In the case of higher order matrix, the Jacobi method is used. However, in this paper the matrix is a second order matrix. So inclination can be obtained by the procedure of equations (4) and (5).

$$\kappa = \frac{\sigma_{xy}}{\sigma_{xx} - \sigma_{yy}}, \tag{7}$$

$$\theta = \sin^{-1}\left\{\frac{1}{2 - 4\kappa}\left(1 - \sqrt{1 - 4\kappa(1 - 2\kappa)}\right)\right\}, \tag{8}$$

θ means the inclination of the needle from the vertical axis, and the counterclockwise rotation on display is the positive direction.

4 EXPERIMENT

The experiment to confirm the performance of proposed method was conducted. After confirming the vertical condition of the needle by the conventional method, the needle is tilted by the robot. Then the angle is measured by the proposed method. TSK guide needle with size of 19G 149 mm manufactured by Task Corporation was used in this experiment. The merge image and extracted region are shown in Fig. 13. The robot has position with $\phi_A = 1$ degree and $\phi_B = 1$ degree in this figure. Also, table 1 shows comparison of measured angles of needle. The robot take a position with $0 \le \phi_A \le 1$ [deg] and $0 \le \phi_B \le 1$ [deg] in this experiment. Because angles larger than 1 degree can be visually distinguished with human eyes. Although the expected trend in measuring angles was obtained, there still remains offset errors less than 0.31 degree.

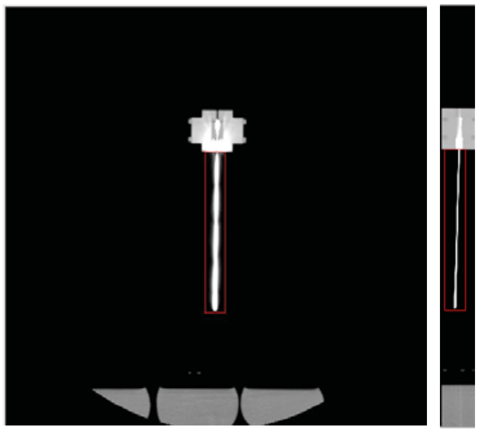

Fig. 13. Result of extraction of area including needle in experiment. Here, needle has inclination with angle $\phi_A = 1$ degree and $\phi_B = 1$ degree.

Table 1. Comparison of measured angles of needle: Here ϕ_A and ϕ_B mean angles made by robot position. $\hat{\phi}_A$ and $\hat{\phi}_B$ are measured angles with proposed method.

ID	ϕ_A[deg]	ϕ_B[deg]	$\hat{\phi}_A$ [deg]	$\hat{\phi}_B$ [deg]
1	0.00	0.00	-0.06	-0.21
2	0.10	0.00	-0.01	-0.22
3	0.20	0.00	0.08	-0.17
4	0.50	0.00	0.35	-0.21
5	1.00	0.00	0.92	-0.20
6	0.00	0.10	-0.11	-0.04
7	0.00	0.20	-0.06	0.17
8	0.00	0.50	-0.05	0.63
9	0.00	1.00	-0.13	1.31
10	1.00	1.00	0.82	1.31

5 CONCLUSION

In this paper, we propose a needle angle offset correction method based on principal component analysis based on CT images. The effectiveness of proposed method is confirmed through the experiment.

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