# Needle pose adjustment based on force information with needle puncturing robot\*

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Abstract-In recent years, interventional radiology (IR) which is a medical procedure has been attracting considerable attention. Doctors can perform IR percutaneously while observing the fluoroscopic image, such as CT and MRI images, of patients. Therefore, this surgical method is less invasive. However, doctors are exposed to strong radiation in the case of CT-guidance. In order to overcome this problem, we have developed remote-controlled IR assistance robot. The phenomena that the needle tip deviates from target tissue at the end sometimes occur, even if the needle is aligned with target tissue before puncturing. In this research a method to adjust pose of a needle in lateral direction based on information of force sensor for reducing deflection of needle is proposed. First, deflection of needle was modeled as a simply cantilever beam. Next, pose of needle gripper of robot to reduce the force is calculated. Finally, validity of the proposed method was verified based on the result of phantom puncture experiment.

# I. 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 surgeon conducts IR treatment percutaneously with inserting a needle or a catheter to the patient body. And CT fluoroscopy system, which can show medical images in real time, is superior as a guiding tool for IR. So CT-guided IR is applied to lung cancer treatment, liver cancer treatment, biopsy, and so on [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. According to the opinion of a doctor, the minimum size of cancer is 5 [mm]. Therefore an operator must puncture a needle carefully and accurately. In addition, operators are exposed to radiation during CT fluoroscopy because operators conduct procedure close to the CT gantry.

In order to prevent radiation exposure, operators wear radiation protection aprons and handle a needle using a forceps which is useful to make distance between their hand and CT radiography plane. However, it is impossible to prevent radiation exposure completely. Then some medical robots are developed in order to make radiation expose zero with a robot which have high accuracy of position such as AcuBot[2], CT-Bot[3] and MAXIO[4]. These robots aim to



Fig. 1. Concept of Robotic IR



Fig. 2. Schematic Diagram

support operators to insert a needle as CT-guided puncture. However, Zerobot, which is developed by our research group, aims to conduct whole process from positioning robot to inserting a needle by remote-control.[5] And our concept of robotic IR is shown in Fig.1. But there is a problem for such process by robot. The problem is deflection of needle during puncture.

Many groups have studied deflection of needle and living bodies in a puncturing robot, and many models and sim-

<sup>\*</sup>This work was not supported by any organization

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Fig. 3. Appearance of Zerobot

ulation methods describing the interaction between a living body and a needle have been proposed, but none has yet been established as a standard model describing the interaction between a needle and a living body.[6]

In addition, a method has been proposed in which the puncture path follows the target trajectory in real time. But it is difficult to perform vision-based puncture path tracking control because of the problem that the resolution of the CT image is low. Therefore, in this research, we propose a puncture angle adjustment control method based on a force sensor that does not feed back the information due to the image of the needle during puncture. We constructed a model under the assumption influence of organs ignored. The shape of the needle is estimated using the model, and calculate the deviation from the target route. After that, puncture is proceeded while controlling the root of the needle in the CT radiography plane so that the tip of the needle faces the target. A schematic diagram of this system is shown in Fig.2. In implementing the puncture angle adjustment control method, the condition listed as follow should be kept.

- 1) At starting puncture, the target tumor exists on the extension line of the central axis of the needle
- The position of the target tumor is stationary without being affected by body motion or strain of the living body

Based on above conditions, the desired pose to start puncturing needle to human body is calculated. Also, joint angle of robot is calculated according to inverse kinematics. In remote center control mode, target tumor is set as center of motion. Robot motion is restricted as needle always looks toward center of motion. By combination of remote center motion and proposed method, force in lateral direction is suppressed in order to reduce deflection of needle. In this article, puncture accuracy is compared in the cases where proposed method is used or not used.

# II. ZEROBOT

The appearance of the developed Zerobot and the enlarged view of end effector are shown in Fig.3. It has five DOF for needle tip position and needle direction, and has one DOF for puncturing direction. Six actuators are located in the machine. Four linear actuators (X, Y, Z and puncturing axes directions) and two rotational actuators (around the X and Y axes) are included.

Because of a method to reconstruct image by CT equipment, if a metal part was in the gantry, incorrect image called artifact will appear on CT image. If artifact appears, patient's internal image will be obscured and trouble will occur on an surgical operation. Therefore, metal parts cannot be used on needle gripper. Accordingly parts are made of engineering plastic, which is radiolucent material.

#### III. DEFLECTION MINIMIZING CONTROL

# A. Bend of the needle at the time of the living body puncture

In the case of manual puncture, a doctor can flexible adjust the direction of deflection needle. Because the doctor can estimate trajectory of deflection of needle, he can bend the form of needle to optional one with his tactile sense. On the other hands, Zerobot has currently no force feed back control in real time because of safety against sensor noise. Therefore, in the robot puncture procedure, deflection of needle is one of the major problems. Deflection of the needle at the time of living body puncture are explained. Figure4 shows a photograph of an animal puncture experiment using a pig.[7] Figure5 shows the CT image of puncture of pig's lung. Deflection  $\delta$  occurs with the needle due to the elasticity of the living body at the time of puncture, and it can be confirmed that the needle direction deviates from puncture axis as the needle is inserted deeper. Due to this influence, even if needle directions aligned with puncture axis at initial condition, needle tip sometimes cannot reach the target tumor at end. So the doctor has to correct the posture of needle when deviation overcomes permissible amount. Once deflection of needle occurs, a situation where the direction of Zerobot's puncture axis does not match the direction of insertion of the needle continues. Under that situation, the needle tends to move to the direction of the needle tip so that deflection of needle tends to grow as the puncture axis is driven. While deflection grows, although the needle tip rarely arrives at target tumor, a deflection is not nearly generated in the convenient direction. Furthermore, since viscoelasticity and inhomogeneity of a living body are individual differences greatly, parameters and structures are different for each organ, so it is generally difficult to predict the growth condition of deflection. Therefore, it is desirable that direction of needle is aligned with desired puncture axis. Also, it is desirable that needle is inserted under a situation where deflection is hard to grow. In this section, the operation method for minimizing the force in the lateral direction of the needle, the model of needle deflected by force applied on certain point of needle, and the result of the experiment for minimizing the deflection force using the phantom are described.



Fig. 4. Environment of animal puncture experiment



Fig. 5. Lung puncture

## B. Operation flow

The deflection minimizing control is executed in the following steps.

1) Estimation of needle shape

When the force in lateral direction is applied to a part of the needle, the shape of the needle is estimated based on the model in Fig. 6.

- 2) Calculation of desired pose Based on the estimated shape, pose of root of needle are calculated to minimize the force  $F_y$  in the deflection direction.
- 3) Decision of robot pose



Fig. 6. Deflection model with target tumor. C is the target trajectory of the root of the needle controlled by tumor-centric remote center control. Therefore, direction of puncture axis always faces the target tumor.

From the obtained desired pose, desired joint angles are calculated by using inverse kinematics.

- 4) Update target value sequentially
  - Even if deflection of needle is suppressed in allowable range, it grows along with depth of needle insertion. Because force sensor has limitation in resolution of measured force, and also approximate model is adopted. Therefore, during needle inserting operation, pose adjustment should be conducted, according to estimated deviation.

# *C.* A needle deflection model and desired pose for minimizing deflection

As mentioned in the previous section, physical properties of organs in living body different. Therefore it is difficult to create a precise model that can be generally applied. Therefore, in this paper we proposed a simple model which describes deflection of needle against applied force. When calculating deflection of needle, it is assumed that a concentration load is applied to the needle only at the puncture point. At this time, the statics relationship between the needle and the phantom can be modeled as a cantilever with concentrated load. The relationship between deflection force  $F_y$  [N], displacement by the deflection  $\delta$  [mm], length of the part inserted in the phantom of the needle  $l_{in}$ [mm] and the length of the needle  $l_E$  [mm] shown in Fig.6 are calculated (1)(2). And, in this paper, the force applied in depth direction ( $X_f$  axis) is not considered.

$$I = \frac{\pi d^4}{64} \tag{1}$$

$$\delta = \frac{F_y \left(l_E - l_{in}\right)^3}{3EI} \tag{2}$$

Here, E is the Young's modulus of the needle [MPa], I is moment of inertia of area of the needle [mm<sup>4</sup>] and d is the diameter of the needle [mm].  $F_y$  is measured force along  $Y_f$  axis. Next, in addition to deflection of needle, the model includes with the position of target tumor. In the Fig.6,  $l_{in}$ ,  $l_{punc}$ ,  $l_E$ , and  $l_{rem}$  mean the current puncture amount, the expected puncture amount, the needle length, and the puncture amount to the target respectively. The puncture amount to the target  $l_{rem}$  can be expressed as follows

$$l_{rem} = l_{punc} - l_{in}.$$
 (3)

Desired position  $(y^*, z^*)$  is calculated as (4)(5), that satisfy the condition where needle direction is always directed toward center of tumor.

$$y^* = y_t - (l_{rem} + l_E)\sin\phi_A^*,$$
 (4)

$$z^* = z_t + (l_{rem} + l_E) \cos \phi_A^*.$$
 (5)

Here, the desired rotation angle  $\Delta \phi_A$  and the desired posture  $\phi_A^*$  are described as

$$\Delta \phi_A = \tan^{-1}(\frac{\delta}{l_{punc}}), \tag{6}$$

$$\phi_A^* = \phi_{A_0} + \Delta \phi_A. \tag{7}$$

The desired position  $(y_t, z_t)$  is calculated as

$$y_t = y_0 + (l_{rem} + l_E)\sin\phi_{A0},$$
(8)

$$z_t = z_0 - (l_{rem} + l_E) \cos \phi_{A0}.$$
 (9)

By above mentioned, the desired pose  $(y^*, z^*, \phi_A^*)$  is obtained. Actually, when puncturing the elastic body with a needle, it is expected that distributed load is applied to the needle.

#### IV. AUTOMATIC PUNCTURE SEQUENCE

A flowchart of the automatic puncturing is shown in Fig.7. In the flow chart, after inserting a needle with 10 mm depth, a robot waits 3 seconds and measure force sensor data. Based on force sensor data,  $E_{punc}$  is calculated by (10), and the robot judges whether to adjust position.  $E_{punc}$  is illustrated in fig.8, and means estimated distance between tumor center and tip of reached needle. And the  $\theta$  in both of (10) and fig.8 is slope-deflection calculated by formula of cantilever. That formula is shown by (11).  $(l_E - l_{in})$  in (11) is a length from puncture point to root of needle, because this equation is calculated based on assumption that needle in living body is straight.

$$E_{punc} = |\delta + l_{punc} \sin \theta| \tag{10}$$
$$-F_u (l_E - l_{in})^2 \tag{11}$$

$$\theta = \frac{-F_y(l_E - l_{in})^2}{2EI} \tag{11}$$



Fig. 7. Flow chart of the automatic puncture control



Fig. 8. Definition of  $E_{punc}$ . Estimated needle path is based on assumption that needle goes straight toward direction of deflection angle  $\theta$ .

### V. AUTOMATIC PUNCTURE ACCURACY VERIFICATION EXPERIMENT

#### A. Experimental procedure

In order to verify the effectiveness of deflection minimizing control and puncture accuracy, a phantom puncture experiment was performed under a CT equipment. Two kinds of biopsy introduction needles which a needle length of 114 mm and a needle diameter of 17G and 19G were used. The phantom is a commercially product for training of IR-CT. That has ribs and organs with homogeneity. However, when compared with actual living organisms, it has a fairly homogeneous structure, and skin slippage is not reproduced. As a result, deflection by skin misalignment or inhomogeneity when puncturing the living body hardly occurs. Therefore, in this experiment, the deflection state was intentionally created, and an experiment was performed assuming a situation where the puncture point shifted due to skin slippage. The types as follow experiments is divided into two.

- Experiment A (Simple insertion) The robot punctures to target without deflection
- minimizing control. Experiment B (Automatic insertion)

The robot punctures to target with deflection minimizing control.

Both Experiment A and Experiment B were performed with 17G needle and 19G needle, respectively, we conducted four kinds of experiments in total. Those experiments were performed three times in each case. The shape of the needle and the distance between the needle tip and the target were measured using the CT image obtained. The target was a 1 mm diameter tungsten ball embedded in the phantom. A tungsten ball was implanted at a depth of 77 mm from the surface of body, since the depth is length for reachable to perform the procedure using a 114 mm needle.

#### B. Experimental Results and Discussion

Sequential CT images in both case of simple insertion and automatic insertion are shown in Fig.9. Black shadow can be seen on each CT image, that appears on extended line of needle due to metal artifact. It can be confirmed that distance from black shadow to target point is larger in the case of simple insertion than that of automatic insertion. On the other hand, automatic insertion realizes motion to adjust pose of needle toward a target during insertion. Finally, tip



Puncture depth [mm]

Fig. 9. Appearance of puncture experiment on CT images. (a) is the case of puncture without control and (b) is the case of automatic puncture control.

of needle reaches the target. The number in the upper left of the CT image in Fig.9(b) means how many times deflection minimizing control was performed in each puncture depth.

Manakan	N II.	There a	Distance [mm]
Number	Needle	Туре	Distance [mm]
1	19G	Simple insertion	10.819
2	19G	Simple insertion	7.157
3	19G	Simple insertion	7.064
4	19G	Automatic insertion	0.933
5	19G	Automatic insertion	2.667
6	19G	Automatic insertion	1.982
7	17G	Simple insertion	5.901
8	17G	Simple insertion	5.874
9	17G	Simple insertion	5.919
10	17G	Automatic insertion	2.123
11	17G	Automatic insertion	0.933
12	17G	Automatic insertion	1.006
Average			
	19G	Simple insertion	8.466
	19G	Automatic insertion	1.861
	17G	Simple insertion	5.898
	17G	Automatic insertion	1.354

# TABLE I PUNCTURE ACCURACY

Next, the distances between the needle tip and the target after completion of puncture are measured from the CT image, and the puncture accuracy of simple insertion and automatic insertion was compared for each needle diameter. A table of distance between target and needle tip after completed insertion is shown in Table I. In the average column in Table I, it can be seen that proposed method have drastically improved puncture accuracy in both cases. From the fact, it was confirmed that the automatic insertion is superior to the simple insertion in the puncture accuracy in both case of 17G and 19G. In addition, it can be said that the distance from the needle tip to target is kept less than 2.5 mm with automatic insertion, except for Number 5. The distance between the needle tip and the target varies from trial to trial, but the following reason may be considered for this.

1) Error in measurement on CT image

The needle and a tungsten ball appear larger than actual on the CT image, because the image is reconstructed based on the radiation absorption coefficient. And measurement manually specifies the approximate position of the needle tip and a tungsten ball in pixel units, so the measurement value varies depending on how it appears on the CT image. The resolution of the CT image is 0.8 mm per pixel, and the resolution in the depth direction is 0.5 mm.

2) Influence of measurement error of force sensor Variations in the value of the force sensor constantly influence the estimated puncture error  $E_{punc}$ . As a result of this, although the deflection force should have been minimized, the robot was given a wrong force from force sensor, and there is a possibility that the robot has accidentally punctured.

Next, measured force  $F_y$  in the lateral direction by advancing puncture is compared as shown in Fig.10. At the time of



Fig. 10. Transition of deflection force by puncture depth

simple insertion, the force in the lateral direction increases as needle is inserted deeper. On the other hand, in automatic insertion, there is less growth of force in the lateral direction than simple insertion. From this, it is understood that automatic insertion is puncturing while suppressing the growth of deflection. Next, the transition of  $E_{punc}$  when the number of route modifications is maximum and minimum is shown in Fig.11. In the figure, (1) and (3) are CT images before puncture, 2) and 4) are CT images after finishing puncture. Comparing the two, the total puncture time differs by about six times. In Fig.11(a), the value of  $E_{punc}$  converges to 1 mm or less smoothly by puncture angle adjustment, whereas in Fig.11(b), puncture angle adjustment becomes oscillatory from the puncture depth of 20 mm. Puncture angle adjustment continued from there for about 250 seconds, but after that, puncture proceeds relatively smoothly and shows good puncture accuracy. Summarizing the above, it is verified that the proposed deflection minimizing control is effective for improving the puncture accuracy by this experiment, since desired puncture accuracy is achieved with almost all trials.

#### VI. CONCLUSION

The prospect of future research is presented. There are two approaches to the movement of the target position during puncture. The first approach is modeling living tissue. However, as the model of the living tissue is calculated more precisely, the computational complexity becomes larger and it is not suitable for calculation in real time. It is necessary to discuss that precision of the model created. Moreover, there are individual differences in the viscoelasticity parameter and structure of the tissue on the physique of the patient. As mentioned in this paper, it is difficult to create a generally applicable living body model, and it is also a problem how to measure elements with individual differences before surgery. Next, another approach is visual feedback of CT images. The desired position can be obtained more accurately than the calculation based on the living body model, and the calculation load is relatively small. But a patient exposure time becomes the problem, because operation is conducted under the CT equipment. The proper use of force sensor based and vision based control is the future task.

### ACKNOWLEDGMENT

This work was supported by Research on Development of New Medical Devices 15652923 from Japan Agency for



Fig. 11. (a) is an automatic insertion which has lowest number of modification of needle path (17G needle, experiment number 11) and (b) is an automatic insertion which has most number of modification of needle path (19G needle, experiment number 6)

Medical Research and Development, AMED.

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