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Contact prediction with patient using projection of point cloud before robotic IR surgery

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Abstract: There is a surgical method called Interventional Radiology (IR) in which needles are inserted into the body using image diagnostic ways such as CT fluoroscopy and X-ray images to perform treatments. IR has been applied to various treatments including lung cancer treatment, liver cancer treatment, and biopsy. IR surgery has been receiving attention in recent years, because it is less invasive for patient than conventional surgery. Surgeons are currently exposed to strong radiation in the case of under CT-guidance. In order to overcome this problem, we developed remote-controlled IR assistance robot named as Zerobot. During the surgery, the contact of Zerobot with the patient should be avoided. For the purpose of reducing the load of operator, we have been studying an assistance system for alarming the contact between the robot and the patient. In this paper, a method to predict the contact between Zerobot and the patient with projection of point cloud is proposed.

Keywords: Medical robot, Interventional Radiology, Contact prediction

1. INTRODUCTION

There is a surgical method called Interventional Radiology (IR) that surgeons insert needles or catheters into the body of patients by using CT images or X-ray images. IR is applied various surgical methods such as lung cancer, liver cancer and biopsy[1]. Currently, surgeons perform IR operation under CT guidance manually holding a needle to puncture. Also, surgeons must control the position of needle carefully and accurately because tumors are minimum 5mm in diameter. In addition, surgeons are exposed to radiation because they should perform IR close to CT equipment. In order to prevent radiation exposure, surgeons wear radiation protection aprons and handle a needle using forceps, which is useful to make distance between a hand of the surgeon and CT measure plane. However, it is impossible to prevent radiation exposure perfectly. Therefore some medical robots are developed in order to reduce radiation exposure, such as AcuBot [2], CT-Bot [3] and MAXIO[4]. We also proposed robotic IR concept that surgeons operate a puncture robot with the remote control and preform IR so as to reduce the exposure of surgeons. The robot named as Zerobot is developed for needle insertion with the remote control by surgeon is in version 3.1, which is shown in Fig. 1. In our project, in order to seek the problems of Robotic IR system, we have conducted phantom puncture experiment and animal puncture experiment [5].

Currently, a needle is inserted using Zerobot, while the surgeon observes real-time CT image. One of problems in IR with CT device is narrowness of working space as shown in Fig. 2. There is the possibility for Zerobot to contact with the patient. If contact of them occurs, the surgery should be stopped immediately. In order to avoid the contact between Zerobot and the patient during the surgery, it is required to predict the contact condition when path of needle is planned. Therefore, the algorithm to predict the contact condition using projection of point clouds is proposed.

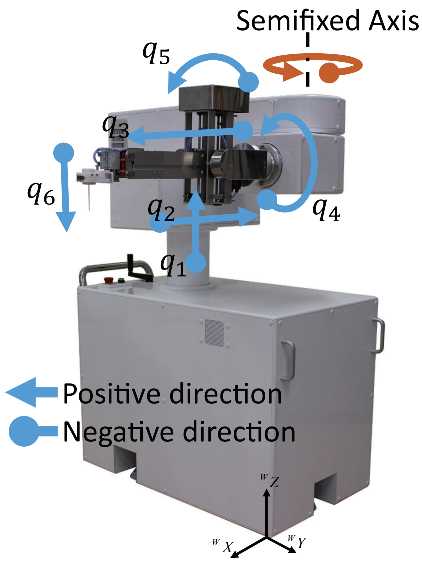


Fig. 1. Appearance of Zerobot

2. ZEROBOT

The overview of Zerobot and structure of end-effector are shown in Fig.1. This robot has five degrees of freedom to decide the pose of the needle, and one degree of freedom to move along puncture direction. As shown in Fig.1, q_1, q_2, and q_3 are linear motion joints. In contrast, q_4, and q_5 are revolving joint, to change posture of needle. Also, q_6 is linear motion joint to insert a needle along with predetermined axis by q_4, and q_5. Due to the property of CT image recon-

† Takayuki Matsuno is the presenter of this paper.

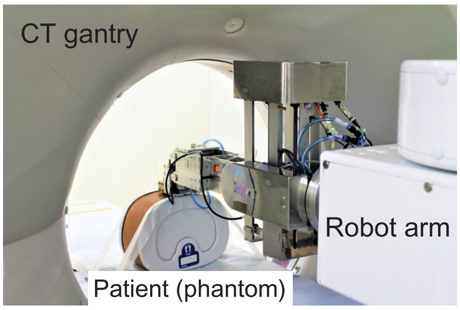


Fig. 2. Working space under CT device

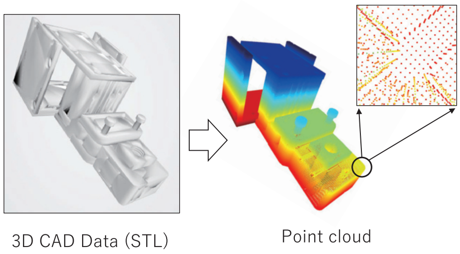


Fig. 3. Conversion of data from STL to point cloud

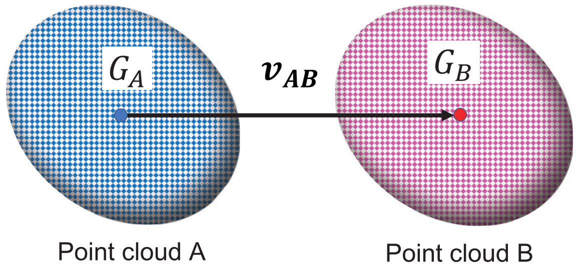


Fig. 4. Point clouds and center of gravities

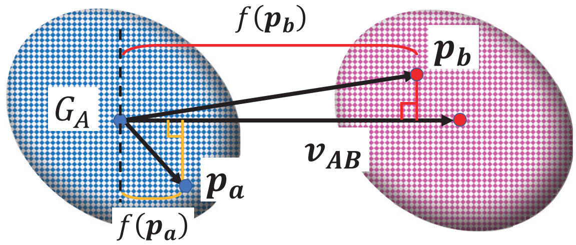


Fig. 5. Inner product

struction, metal parts on CT scanning plane cause artifacts, which are large noise blocks in CT image. It makes difficult to recognize the organs of the patient and prevents continuing surgery. Therefore, actuators and sensors are mounted far from CT scanning plane. It can be realized by applying parallel mechanism to end-effector. That is the advantage of Zerobot against other IR robots. Also, the remote center motion around the needle tip is realized with each axis synchronization.

3. CONTACT PREDICTION ALGORITHM

Contact prediction algorithm is explained in this section.

3.1. Overview of algorithm

There are three stage to predict the contact between a robot and a patient.

1. surface of patient body in volume CT image are converted into points in three dimensional space.
2. Robot parts are converted into points in three dimensional space based on kinematics. The parts of robot are originally expressed with 3D CAD data. In current CAD software, CAD data can be converted into STL data. Then, edge points of STL Data can be picked up by Open3D library in python language [6], as shown in Fig. 3. The set of edge points is called as a point cloud.
3. Contact between points of the patient and points of the robot are predicted using proposed algorithm.

3.2. basis of algorithm

First, a couple of point clouds to calculate contact condition is defined as point cloud A and B as shown in Fig.4. Then, the center of gravity in point clouds $\boldsymbol{G_A}, \boldsymbol{G_B}$ are calculated as equations (1) and (2).

$$\boldsymbol{G_A} = \frac{1}{N_A}\sum_{k=1}^{N_A} \boldsymbol{p}_a(k) \tag{1}$$

$$\boldsymbol{G_B} = \frac{1}{N_B}\sum_{k=1}^{N_B} \boldsymbol{p}_b(k) \tag{2}$$

Here, N_A and N_B are number of points in point cloud A and B. $\boldsymbol{p}_a$ and $\boldsymbol{p}_b$ mean the position of each element in three dimensional space. The vector $\boldsymbol{v_{AB}}$ to connect above center of gravities is defined as Eq.(3).

$$\boldsymbol{v_{AB}} = \boldsymbol{G_B} - \boldsymbol{G_A}. \tag{3}$$

Next, the function to calculate the inner product between a point $\boldsymbol{p}$ and vector $\boldsymbol{v_{AB}}/|\boldsymbol{v_{AB}}|$ is defined as Eq.(4).

$$f(\boldsymbol{p}) = \frac{(\boldsymbol{p} - \boldsymbol{G_A}) \cdot \boldsymbol{v_{AB}}}{|\boldsymbol{v_{AB}}|}. \tag{4}$$

As shown in Fig.5, $f(\boldsymbol{p})$ means the distance of $\boldsymbol{p}$ from $\boldsymbol{G_A}$ along the vector $\boldsymbol{v_{AB}}$. The points $\boldsymbol{p_a^{max}}$ and $\boldsymbol{p_b^{min}}$ are defined as equations (5) and (6) respectively.

$$\boldsymbol{p_a^{max}} = \arg\max_{k \in N_A} f(\boldsymbol{p_a}(k)) \tag{5}$$

$$\boldsymbol{p_b^{min}} = \arg\min_{k \in N_B} f(\boldsymbol{p_b}(k)) \tag{6}$$

$$\tag{7}$$

It can be seen that if the point $\boldsymbol{p_b^{min}}$ is farther than point $\boldsymbol{p_a^{max}}$ with respect to point $\boldsymbol{G_A}$, point clouds A and B are not contact. If there is possibility to contact between those point clouds as shown in Fig. 7, $\boldsymbol{p_b^{min}}$ and $\boldsymbol{p_a^{max}}$ have those elements respectively.

3.3. scheme including iteration

The total scheme including iteration is described in this subsection. Based on inner product introduced in previous

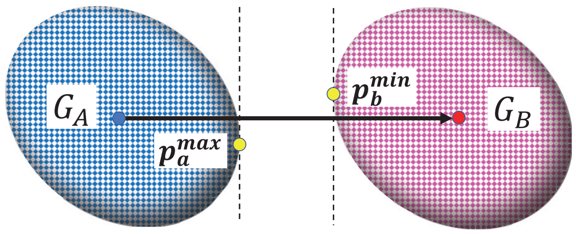


Fig. 6. Definition of points p_a^{max} and p_b^{min}

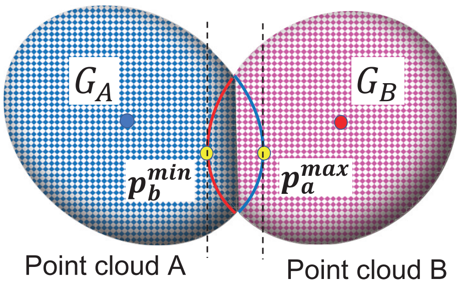


Fig. 7. Condition occurring contact

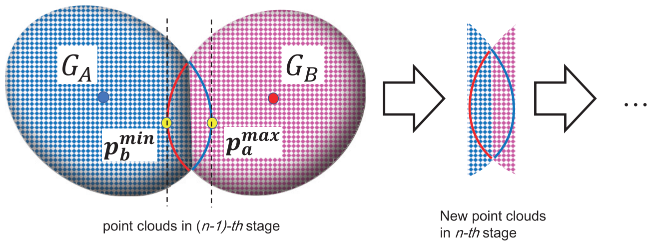


Fig. 8. Iteration and reduced points

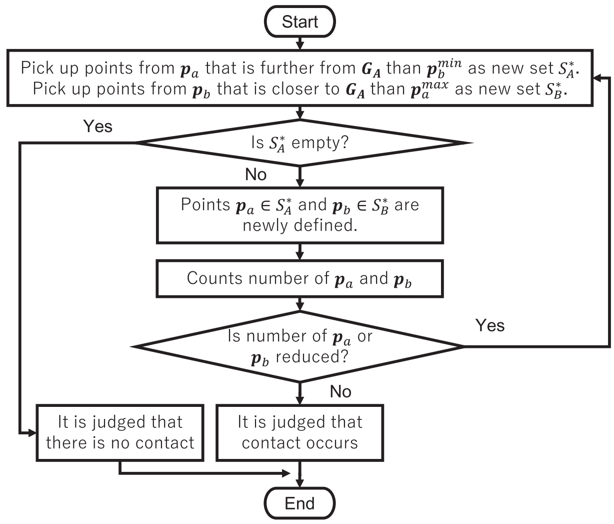


Fig. 9. Flowchart

subsection, the contact of point clouds is predicted using iteration method. Set of point cloud A and B are defined as S_A and S_B respectively. This means $\boldsymbol{p_a} \in S_A$ and $\boldsymbol{p_b} \in S_B$. For the initial condition,

$$S_A^*(1) = \{\boldsymbol{p_a} | f(\boldsymbol{p_a}) > f(\boldsymbol{p_b^{min}})\}, \tag{8}$$
$$S_B^*(1) = \{\boldsymbol{p_b} | f(\boldsymbol{p_b}) < f(\boldsymbol{p_a^{max}})\} \tag{9}$$

can be calculated. If $S_A^*(1)$ is empty, it is judged that there is no contact between point cloud A and B. Otherwise, the calculation is continued for the new sets of point cloud. After the second stage, new point data $\boldsymbol{p_a^{(i)}}$ and $\boldsymbol{p_b^{(i)}}$ are defined as below,

$$\boldsymbol{p_a^{(i)}} \in S_A^*(i-1), \tag{10}$$
$$\boldsymbol{p_b^{(i)}} \in S_B^*(i-1). \tag{11}$$

Here i means iteration number. Then, the calculation introduced subsection 3.2 for new sets of points $\boldsymbol{p_a^{(i)}}$ and $\boldsymbol{p_b^{(i)}}$ is continued. Of course, the center of gravities is also recalcuted as below,

$$\boldsymbol{G_A^{(i)}} = \frac{1}{N_A^{(i)}} \sum_{k=1}^{N_A^{(i)}} \boldsymbol{p}_a^{(i)}(k), \tag{12}$$

$$\boldsymbol{G_B^{(i)}} = \frac{1}{N_B^{(i)}} \sum_{k=1}^{N_B^{(i)}} \boldsymbol{p}_b^{(i)}(k). \tag{13}$$

Here, $N_A^{(i)}$ and $N_B^{(i)}$ are number of points $\boldsymbol{p}_a^{(i)}$ and $\boldsymbol{p}_b^{(i)}$ respectively. It can be explained that this algorithm picks up points, which has possibility to contact other point cloud, using projection based on inner product. And, points out of scope of calculation in both point clouds are deleted during iteration calculation as shown in Fig. 8.

There are two conditions to finish this iteration. One is that $S_A^*(i)$ becomes empty. Other is that $N_A^{(i)}$ equals $N_A^{(i-1)}$. In the later case, proposed algorithm judges that contact occurs. If $N_A^{(i)}$ does not equal $N_A^{(i-1)}$, calculation is continued. The flowchart to show these sequences is shown in Fig.9.

4. EXPERIMENT

So as to confirm the effectiveness of proposed method, the experiment using Zerobot, CT device and CT phantom is conducted.

4.1. Sequence of experiment

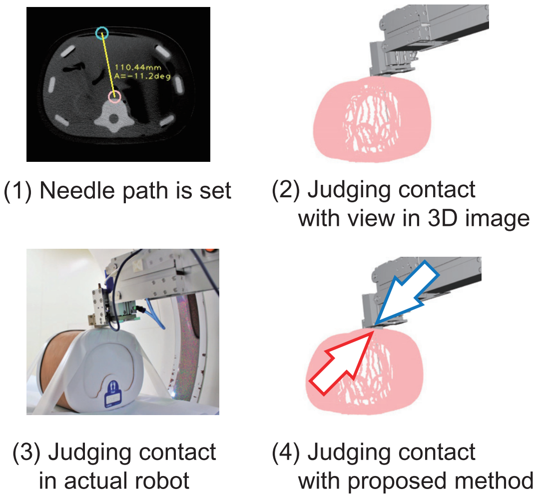
Experimental sequence is shown in Fig. 10. First, the path of needle is set using interface software with scanned CT image as shown in Fig. 10 (1). Secondly, contact condition is judged with viewing using three-dimensional space using Open GL as shown in Fig. 10 (2). Next, the real Zerobot is driven to the desired pose based on path planning. Then, the contact condition is checked as shown in Fig. 10 (3). Finally, contact condition is calculated with proposed method.

4.2. Experimental result

The experimental results are shown in table 1. The experiment is performed in 10 times with various poses, which are realized with joint angles q_4 and q_5. In actual robot, the contact occurs in 5 times. On the other hand, the contact was detected in 3 times with both of the three-dimensional visualization and the proposed algorithm. Experimental index 7 and 9 in table 1 have mismatched results between actual condition and simulation. Proposed method has same result in three-dimensional visualization. This indicated that though the propose method can correctly calculate contact condition, the registration between actual condition and simulation makes mismatched. The mismatch of registration seems to be caused by deflection of arm of Zerobot. Finally, the

Table 1. Experiment result:✓ means contact condition and × means no contact condition.

index	1	2	3	4	5	6	7	8	9	10
Joint angle q_4 [deg]	20.0	-11.2	0.0	8.3	0.0	0.0	-16.9	-45.0	-45.0	-45.0
Joint angle q_5 [deg]	0.0	0.0	-8.8	0.0	0.0	10.5	11.2	0.0	0.0	0.0
State in actual experiment	✓	✓	✓	×	×	×	✓	×	✓	×
State in simulation	✓	✓	✓	×	×	×	×	×	×	×
State in proposed algorithm	✓	✓	✓	×	×	×	×	×	×	×
time to calculate [sec]	0.17	0.17	0.20	0.19	0.18	0.17	0.17	0.19	0.19	0.17



(1) Needle path is set (2) Judging contact with view in 3D image

(3) Judging contact in actual robot (4) Judging contact with proposed method

Fig. 10. Evaluation in experiment

time to calculate the contact condition is less or equal than 0.2 seconds in all cases. It is enough fast to detect the contact of robot in our experimental environment.

5. CONCLUSION

In this paper, in order to avoid the contact between Zerobot and the patient during the surgery, the algorithm to predict the contact condition was proposed. So as to confirm the performance of contact prediction algorithm, experiments using Zerobot and CT phantom were conducted.

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