Precision Compensation of Localization Error in Obstacle-navigation for Inspection Robot

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Abstract—Research on inspection robot for 500kv EHV power transmission lines home and abroad began with great potential applications in the electric industry. Path planning for robot to navigate obstacles based on environments perception is attempted in the present study; moreover, lines localization is the key during navigating obstacles. An analytical localization method is proposed; however, localization error is brought by perception sensors of lines identification, which affects the accurateness of lines localization precision. Precision compensation for the localization error in the kinematics model is represented with a rotation degree of freedom as the same direction as that of the localization error. The simulation and the experiments are carried out with navigating obstacles that the proposed compensation might actually provide an accurate localization precision.

I. INTRODUCTION

The 500kv extra high voltage (EHV) power transmission lines provide main electricity for human life, thus in recent years, the inspection robots has aroused researchers' attention[1] for their practical applications in the electric industry. The research started from the end of 1980s; yet, Sawada[2] developed the earliest inspection robot. Early researchers mainly focused on robots without the navigating ability and the techniques according to literatures. Generally, most inspection robots adopt wheeled mechanism for higher inspection speed[3]. One type of mechanism cannot implement navigating and moving synchronously, while compound mechanism shows enhanced performance on mobility and trafficability[1]. The wheeled mechanism[4-6,8], stepwise crawling mechanism[3] and others can move on the pipeline[7]. The wheel-armed mechanism[11,12,15,17] multi-unit mechanism[13], and bionic arm mechanism[2,9,10,14] etc are the main mechanism to implement obstacle-navigation on the pipeline[7,16].

Path planning of the inspection robot is based on the environments perception to navigate the obstacles; however, perception sensors for identifying the ground lines bring error in, which affects the manipulators of the inspection robot not to grasp the lines, the robot would fall down to the ground without the accurate precision of localizing lines.

This paper thereby presents precision compensation of localizing error during navigating the obstacles for the inspection robot. Firstly, the typical operation environments and the survey objects of inspection operation are confirmed to assist modeling the obstacle space of inspection. Secondly, the motion of navigating the obstacles is planned and an analytical localization method is proposed. Thirdly, a rotation degree of freedom (DOF) exists as the same direction as that of localization error; therefore, precision compensation for localizing the lines in the kinematics model is represented. Finally, the simulation and the experiments of robot navigation are performed to show that the proposed compensation might provide accurate lines localization.

II. OBSTACLE-NAVIGATION PLANNING

Path planning is the basic request for the inspection robot to interactive with the EHV power transmission lines environments. Path planning of the environments model is built with the introduction of the inspection robot system before the before methods of searching reasonable paths are found[18].

A. Inspection Robot System

The inspection robot system is composed of two subsystems, one is the robot working on lines, the other is the ground working station[19]. The mechanical system of the robot on lines could be divided into the mechanism of the robot entity, the manipulators, the auxiliary mechanism, and the housing mechanism. A mobile control station is the ground working station, which can monitor the robot by the wireless transmission system and control the robot by image data analysis. The left is the ground working station and the right is the robot entity on the lines in Fig.1.

Fig. 1. System of inspection robot for EHV power transmission lines

B. Description of Obstacles Environments

In the EHV power transmission lines environments, obstacle-navigation has tough requirements for the inspection robot from environments interference as illustrated in Fig. 2.
1) Definitions: First some symbols have to be presented.

- \( L \) — the length of damper;
- \( M \) — the length of the damper on the lines for mounting;
- \( D \) — the diameter of the damper;
- \( N \) — the length of the clipper;
- \( P \) — the height from the top of the clipper to the tension string;
- \( e \) — the empirical value (It is assigned a value in 5~10mm).

The width of the clipper can be expressed by a maximum estimation of 100mm in width.

2) Expressions for Obstacle Space: The space of the damper and the clipper should be as followed. If the suspension rods of the damper are neglected, the space of the damper is

\[
s_1 = \pi (0.5D + e)^2 (L + e)
\]

The maximum diameter of the lines chosen is 18mm, and then double of \( e \) is added to the height. Thus the space of the clipper is

\[
s_2 = 100(18 + 2e)N
\]

As the lower limit of the state space, \( s_c \) is the minimum navigation space for the robot to cover the clippers. The upper limit is that the robot cannot go beyond the bottom of the tension strings. Then the upper limit value is

\[
s_c = 100LN
\]

Thus the space of the clipper for the robot is a range, which can be expressed

\[
s = (100(18 + 2e)N, 100LN)
\]

3) Navigation Space: A space set \( s \) for the robot to pass the obstacles can be a uniform format to attempt autonomous control procedure.

\[
s \subseteq s_1 \cup s_2
\]

C. Procedure of Obstacle-navigation Planning

Obstacle-navigation planning is in compliance with the flow chat as illustrated in Fig. 3. And it is also the motion flow of navigating obstacles.

III. ERROR ANALYSIS

The diameters of the transmission lines are 14mm~18mm while the spot size of the identification sensors is 2mm in diameter. This error brought by the laser sensors for identifying lines can be ignored in no case. The precision of localizing lines would be decreased by the error for the handle on the manipulator would not grasp the ground lines, which provokes the robot system on the line to fall to the ground. It is dangerous for the robot to fall off without any explanations.

A. Relationship of Analytical Localization Method

The motion flow of navigating procedure of Fig.3 is framed to figure out three difficulties: balancing, identifying and localizing the lines during navigation, in which localizing the lines is the key by environment models and navigating gaits. An analytical localization method has been proposed to solve the key problem. The method is to project the three-dimension space relationships of localizing lines into the two-dimension geometric plane and resolve their projecting relationships. And then the two-dimension geometric relationships are reduced into the three-dimension space to solve localizing lines. It is supposed in the situation without wind and other disturbances that localizing lines can be stable. Based on the perception precision of obstacle sensors as illustrated in Fig.4, the distance between the angle of rotation center and the center of front wheel is 150mm. Thus the angle of rotation on the shift tower can be confirmed, which is defined as \( \theta \) by

\[
\theta = \arctan \frac{R_1 \cos \alpha_2 - R_2 \cos \alpha_1}{R_2 \sin \alpha_2 - R_1 \sin \alpha_1}
\]

\( \theta \) — angle of rotation on shift tower;
\( R_1, R_2 \) — radii of the navigating handle center line to front and back sensors;
\( L_0 \) — distance between angle of rotation center and the center line of navigating handle;
\( \alpha_1 \) — a rotation angle when the navigating handle “identifies” the lines;
\( \alpha_1' \) — error angle of \( \alpha_1 \);
\( \alpha_2 \) — a rotation angle when the navigating handle “localizes” the lines;
\( \alpha_2 \) — error angle of \( \alpha_2 \);
\( \beta \) — rotation angle of localization compensation.

\[
L_0 = 15 + \frac{8}{\cos \theta}
\]

\[
\Delta \alpha_1 = \alpha_1 - \alpha_2, \quad \Delta \alpha_2 = \alpha_2 - \alpha_2 \; ;
\]

\[
\Delta \alpha_1 = \theta - \alpha_1, \quad \Delta \alpha_2 = \alpha_2 - \theta \; ;
\]

\[
\gamma = \Delta \alpha_2,
\]

\[
= \arcsin[\frac{15}{R_2} \sin \theta] - \arcsin[\frac{15}{240} \sin \theta]
\]

\[
= \arcsin[\frac{15}{R_2} \sin \theta] - \arcsin[0.0625 \sin \theta]
\]

\[
\beta = \theta - \arcsin[0.0625 \sin(\pi - \theta)]
\]

\( \text{B. Error Analysis} \)

There is a perception range of identification sensors as \( \Delta \alpha_1 \), while \( \Delta \alpha_2 \) and \( \sin \Delta \alpha_2 \) are small quantities approaching zero, and \( \cos \Delta \alpha \approx 1 \).

\[
R \cos \alpha_2 - R \cos \alpha_1 \approx \frac{(R_k - R)}{R} \cos \alpha_1
\]

\[
R \sin \alpha_2 - R \sin \alpha_1 \approx \frac{(R_k - R)}{R} \sin \alpha_1
\]

If \( \sin \alpha_2 = k_1 \sin \alpha_1 \), \( \cos \alpha_2 = k_2 \cos \alpha_1 \), \( k_1, k_2 \) are the ratio coefficients of approaching 1.

\( (R_k - R) < 30 \), for the distance between the two hands sensors on the manipulator are less than 30 mm; while 30 mm is a small quantity for the \( R_k \) and \( R \). \( \alpha_2 < \alpha_1 \), \( k_1 \geq 1 \), and \( k_2 < 1 \); therefore, , and in formula (12) is a tiny value nearly equaling to \( \pm \tan \alpha_1 \).

The error of identifying lines during navigating the obstacles can be theoretically simplified or ignored; however, the error affects the precision of localizing lines much because the diameters of the transmission lines are only 14~18 mm.

2:14=1:7=14.29% and 2:18=1:9=11.11%.

Tthereby, the identification error accounts for [11.11%, 14.29%] of the perception range of localization if there is no localization compensation. The error thus must not be neglected.

\( \text{C. Simulation of Analytic Obstacle-Navigation} \)

Based on the kinematics models and the geometric environments, the simulation of identifying and localizing the lines during the obstacle-navigation planning is performed to confirm the identification and localization space as illustrated in Fig.5.

The identification space with the curved face has a leap when it is zero angle of the tower as shown in Fig.5.(a), which means that the rotation angle information of the one identifying sensor confirms a localizing angle; hence, there are two corresponding localization angle curves as illustrated in Fig.5.(b).

\( \text{IV. PRECISION COMPENSATION} \)

Fig. 6. Sketch of the robot mechanism
One cause of applying the kinematics model to compensate the precision is that the error brought by the identifying sensors cannot be avoided, which would always be in the obstacle-navigation planning if the identification method is used. One reason is that the identifying sensors must have their own measurement range and precision; thus, the identification error cannot be avoided. Another reason of the precision compensation is the error brought by the identification segment, which leads to the inaccuracy precision of localizing the lines in the rotation angle by the obstacle-navigation planning algorithm. There is a rotation degree of freedom, which is the same rotation direction to the error rotation brought by the identifying sensors.

For simple, \( \sin \theta = s \theta \), \( \cos \theta = c \theta \); \( \sin(\theta - \theta_j) = s \theta_j \), \( \cos(\theta - \theta_j) = c \theta_j \), \( j = 1, 2, 3, \ldots \)

### TABLE I

<table>
<thead>
<tr>
<th>Link</th>
<th>( a_{i,j} )</th>
<th>( a_{i,j} )</th>
<th>( d_{i,j} )</th>
<th>( \theta_{i,j} )</th>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>3c0</td>
<td>90</td>
<td>41t</td>
<td>( \theta_j )</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>180</td>
<td>m150</td>
<td>0</td>
</tr>
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<td>0</td>
<td>1t+150</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>3c0</td>
<td>90</td>
<td>41t</td>
<td>( \theta_j )</td>
</tr>
</tbody>
</table>

It can be observed that the projection of the localization always in the permitted range of Fig.6.(a) circles.

### A. Precision Compensation Principle

The key of the precision compensation is attempted to put a calibration angle in the rotation drive of the code disk on the manipulators as the precision compensation of localizing the lines, which value and direction would equal to the error angle brought by the identification segment. The rotation degree of freedom can be observed in the kinematics model as shown in Tab. I and \( \mathcal{T} \). The code disk of rotation drive is consequently divided \( 2 \pi / 2048 \) into 2048 portions, which precision can be 0.003rad \( (0.176^\circ) \).

\[
\frac{2 \pi}{2048} \approx 0.003 \text{rad} = 0.176^\circ
\]

The design criterion and operation have required that the localizing error must not exceed 2mm, that is to mean, the localizing lines with error brought by the identification segment can not pass the precision of \( \frac{2}{0.5(R_6 + R_7)} < 0.03 \text{rad} = 0.176^\circ \).

### B. Precision Compensation Simulations and Localizing Experiments

The simulation of localizing the lines with the error and the precision compensation has been presented in Fig.6 (a), based on the prototype data of the inspection robot. Fig.6. (a) has three-colored circles, the red and the green circle respectively express the lines localization with the error brought by the identification segment; moreover, the red circle is the upper bound of the localization space while the green one is the lower bound of that. The blue circle means the localization with the precision compensation in the kinematics models, which can be observed that the localization with the compensation is more accurate than that without the precision compensation. The lower bound expression is

\[
x_l = 0.5(R_6 + R_7) \sin(t) - 0.5[R_6 - R_7] \sin(t)
\]

\[
y_l = 0.5(R_6 + R_7) \cos(t) - 0.5[R_6 - R_7] \cos(t)
\]

\[
z_l \leq 240
\]

The upper bound expression is

\[
x_u = 0.5(R_6 + R_7) \sin(t) + 0.5[R_6 - R_7] \sin(t)
\]

\[
y_u = 0.5(R_6 + R_7) \cos(t) + 0.5[R_6 - R_7] \cos(t)
\]

\[
z_u \leq 240
\]
the left figure is that the inspection robot were been lift up to the tower of the 500kV EHV power transmission lines in the study, while the right one is that the robot were inspecting on the lines.

V. CONCLUSION

The manipulator of inspection robot and robot entity can perform obstacle-navigation planning based on environments perception for robot to navigate obstacles.

Three types of objects as inspection obstacles are summarized their varieties and particularities by analysis of particular EHV operation environments; moreover, mathematical models of obstacles space are presented.

Motion flow of navigation is framed by environment models and navigating gaits to figure out three difficulties: balancing, lines identification and localization during navigation, in which lines localization is the key. An analytical localization method has been proposed to solve the key problem of localizing lines.

Theoretically analysis of the localization error brought by identification is tiny, but the practically analysis argue that though it can be tiny, it can never be ignored. Thus the precision compensation of localization can be performed to 0.003rad (0.176°).

The rotation degree of freedom is as the same direction as that of localization error, precision compensation for lines localization in kinematics model is utilized to assist localization. Simulation of line localization with error and compensation has shown that the precision compensation of localization error are always in the restricted localizing circles. Experiments of robot navigation in laboratory and field are also performed to show that the proposed compensation provides accurate lines localization.

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