Development of a Vision-based Position Estimation System for the Inspection and Maintenance Manipulator of Steam Generator Tubes a in Nuclear Power Plant

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Abstract: A vision-based tool position estimation system for the inspection and maintenance manipulator working inside the steam generator bowl of nuclear power plants can help human operators ensure that the inspection probe or plug are inserted to the targeted tube. Some previous research proposed a simplified tube position verification system that counts the tubes passed through during the motion and displays only the position of the tool.

In this paper, by using a general camera calibration approach, tool orientation is also estimated. In order to reduce the computation time and avoid the parameter bias problem in an ellipse fitting, a small number of edge points are collected around the large section of the ellipse boundary.

Experiment results show that the camera calibration parameters, detected ellipses, and estimated tool position are appropriate.

Keywords: Tool position estimation, Steam Generator, Tube sheet, Ellipse detection, Camera calibration

1. INTRODUCTION

The steam generators used in nuclear power plants typically have a tube sheet into which the ends of thousands of heat exchanger tubes are secured. Heated primary fluid from the nuclear reactor is passed through the tubes to exchange the heat with the secondary working fluid that drives the turbo-machinery used to generate electricity.

Since the primary fluid is radioactive, the heat exchanger tubes are subject to inspection and repair during the overhaul when the power station is off-line for repairs and maintenance.

The defective tubes found from the inspection task are typically plugged to seal the end of the tube so as to prevent leakage of the primary fluid to the secondary working fluid.

To perform the inspection or plugging tasks, a robotic manipulator is installed within the steam generator bowl and the positions and orientations of the manipulator base are calibrated. After the calibration, the end effector of the manipulator moves to the target tube position and a human operator convinces himself of the position of the end effector through the image captured from the camera mounted on the inspection probe guide. When the position of the end effector is appropriate, the inspection probe or plug from the end effector is inserted into the desired tube.

However it could be possible for the end effector to be located under the neighboring tube of the intended target tube because the deflections of the manipulator could not be calibrated completely. The mis-positioning of the probes or the repair tools into the tube other than the intended target tube poses substantial safety implications.

To cope with such a problem, an independent tube position verification system was introduced which counts the tube ends during the motion under the tube sheet surface and displays the position of the end effector.

But this system can display the position only with integer number, so it could not show which tube is nearest the other tube when the end effector is between the two tubes. In addition to this, it considers only the relative position between the tube sheet and camera, not the relative position between the camera and end effector.

The orientation of the end effector is also important for inserting the probe or plug into the intended target tube but this system provides no explicit information about the orientation of the end effecter.

In this paper, we explain about the position estimation system for the end effector which provides position and orientation information of the end effector relative to the tube sheet.

2. POSITION AND ORIENTATION REPRESENTATION

Fig. 1 (a) shows the real-sized test mock-up of the steam generator bowl imitating that of the Kori-I nuclear power plant in Korea. The circular tube ends are arrayed with rectangular shapes in the tube sheet as shown in Fig.1 (b).

Fig. 2 depicts the coordinate frames for describing the position and orientation estimation process we present.

The world coordinate frame {S} is located on the tube sheet. The location of the center of each tube is represented with respect to the {S} as follows:

$$x_S = p \cdot r, \quad y_S = p \cdot c, \quad z_S = 0\,. \tag{1}$$

Where p , r and c represent the pitch, row and column number of the tube respectively.

The camera coordinate frame {C} is fixed onto the camera , with the z_C axis coinciding with the optical axis, and the x_C , y_C axes parallel to the image x_I , y_I axes. The tool coordinates frame {T} is fixed onto the tool of the robot and as the robot moves, it moves with the end effector. The origin of {T} is the center of the circle of the probe guide and the z_T axis is parallel to the direction of the probe guide.

Let an arbitrary point P is represented by P_S , P_C , P_T with respect to {S}, {C}, and {T} respectively.

${}^C H_T$ defines the homogeneous coordinate transformation matrix from {T} to {C} relating P_T with P_C as follows:

$$P_C = {}^C H_T P_T\,. \tag{2}$$

${}^C H_S$ defines the homogeneous coordinate transformation matrix from {S} to {T} relating P_S with P_C as follows:

$$P_C = {}^C H_S P_S\,. \tag{3}$$

The position and orientation of the tool with respect to the {S} can be represented by the homogeneous transformation matrix ${}^S H_T$, which can be obtained as follows:

$$ {}^S H_T = {}^S H_C \, {}^C H_T = {}^C H_T^{-1} \, {}^C H_T \,. \tag{4}$$

We can write the form of ${}^S H_T$ as

$$ {}^S H_T = Trans(T_X, T_Y, T_Z) Rot(z,\alpha) Rot(y,\beta) Rot(x,\gamma) $$
$$ = \begin{bmatrix} c_\alpha c_\beta & c_\alpha s_\beta s_\gamma - s_\alpha c_\gamma & c_\alpha s_\beta c_\gamma + s_\alpha s_\gamma & T_X \\ s_\alpha c_\beta & s_\alpha s_\beta s_\gamma + c_\alpha c_\gamma & s_\alpha s_\beta c_\gamma - c_\alpha s_\gamma & T_Y \\ -s_\beta & c_\beta s_\gamma & c_\beta c_\gamma & T_Z \\ 0 & 0 & 0 & 1 \end{bmatrix} . \tag{5}$$

Where (T_X, T_Y, T_Z) is the coordinate of the origin of {T} with respect to the {S}, and α, β, γ are roll, pitch, and yaw angle respectively.

The purpose of the position estimation system we present in this paper is to obtain the position of the tool, (T_X, T_Y, T_Z), and the orientation of the tool, (α, β, γ).

To compute ${}^S H_T$ from Eq. (4), we should get ${}^C H_T$ and ${}^C H_S$.

${}^C H_S$ is usually referred to as the extrinsic parameter in camera calibration problems that is dependent on the movement of camera.

Using Tsai's calibration method, a point represented by (x_S, y_S, z_S) with respect to {S} is mapped into the image coordinate (x_I, y_I) through a distorted image coordinate (x_D, y_D) as follows:

$$ x_C = f \frac{h_{11} x_S + h_{12} y_S + h_{13} z_S + h_{14}}{h_{31} x_S + h_{32} y_S + h_{33} z_S + h_{34}} , \tag{6}$$

$$ y_C = f \frac{h_{21} x_S + h_{22} y_S + h_{23} z_S + h_{24}}{h_{31} x_S + h_{32} y_S + h_{33} z_S + h_{34}} , \tag{7}$$

$$ x_C = x_D (1 + \kappa R_D{}^2) , \tag{8}$$

$$ y_C = y_D (1 + \kappa R_D{}^2) , \tag{9}$$

$$ R_D{}^2 = y_D{}^2 + y_D{}^2 , \tag{10}$$

$$ x_I = \frac{s_X}{d_X} x_D + C_X , \tag{11}$$

$$ y_I = \frac{1}{d_Y} y_D + C_Y . \tag{12}$$

Where f is effective focal length, or image plane to projective center distance, and k is radial lens distortion coefficient, d_X is the estimated distance between the adjacent sensor elements in a scan line direction, and d_Y is the distance between the adjacent sensor elements in a vertical direction.

In the above equations, s_X is the scale factor compensate for the scanning and acquisition timing uncertainty, (C_X, C_Y) is the coordinate of the origin of {C} with respect to the image coordinate frame {I}.

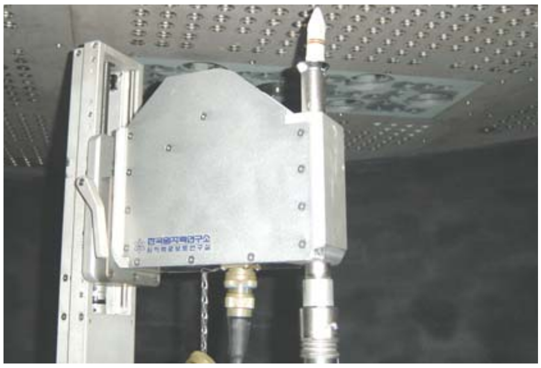
Among the above parameters, d_X and d_Y can be known as priori, but five parameters, f, k, s_X, C_X, C_Y, usually referred to as the intrinsic parameters should be calibrated.

In order to obtain the intrinsic and extrinsic parameters, data set consisting of the coordinate pairs of (x_S, y_S, z_S) and (x_I, y_I) of the calibration target points should be provided.

As mentioned in reference [2], if a data set used for the camera calibration process is coplanar, all the extrinsic and intrinsic parameters could not be determined.

Because the tube sheet is a semi-circular plane, the data set obtained from the center of the tube ends is coplanar, but extrinsic parameters ${}^C H_S$ can be determined if we calibrated the intrinsic parameter using a non-coplanar calibration target in priori.

(a) Test mock-up of steam generator and manipulator



(b) Tube sheet and inspection probe

Fig. 1 Test mock-up of steam generator and tube sheet

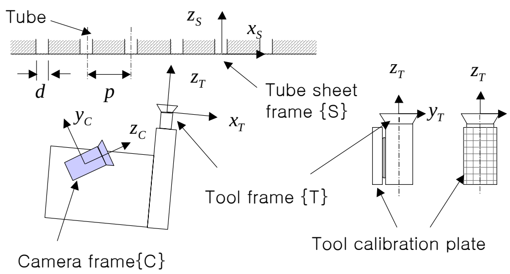


Fig. 2 Coordinate frames

3. ELLIPSE EXTRACTION

As mentioned above, to estimate the position and orientation of the tool with respect to the tube sheet, ${}^C H_T$ and ${}^C H_S$ should be computed. Because the geometric relation between the camera and the tool is constant, ${}^C H_T$ is also constant. But ${}^C H_S$ is varying along with the movement of the manipulator on which the camera is fixed.

In order to perform a real-time computation of ${}^{C}H_{S}$, a data set consisting of the coordinates of points on the tube sheet with respect to {S} and the image coordinates of the corresponding points with respect to {I} should be generated in a real time manner.

The center point of the circular tube end can be easily distinguished from the other points in the tube sheet to some extent. And if the row and column number of the tube end in the image captured from the camera is known, the coordinate of the center point of the tube end with respect to {S} can be obtained from Eq.(1).

So a computation method for the coordinate (x_I, y_I) of the center point of the tube end with respect to {I} from the captured image should be provided.

Because the monitoring camera is usually aligned at an angle of about 45 degrees relative to the direction of the probe guide and the probe guide is nearly perpendicular to the tube sheet, the circular tube ends are shown as ellipsoids in Fig. 3(a).

To compute the center point of the tube ends, the edge points of the tube ends are fitted to an appropriate ellipse.

Regarding the importance of ellipses, many different methods have been proposed for their detection and fitting.

The methods based on the Hough transform are robust against noise and outliers among data. In addition, such methods are able to detect multiple primitives at once. Unfortunately, these methods are typically rather slow, memory consuming and not accurate enough.

The other methods based on optimization of an appropriate objective function have the main advantages of speed and accuracy, on the other hand these methods can typically fit only one primitive at a time. So the data has to be pre-clustered before applying the methods.

An ellipse is a special case of a general conic which can be described by an implicit second order polynomial

$$F(x,y) = ax^2 + bxy + cy^2 + dx + ey + f = 0 , \qquad (13)$$

with an ellipse-specific constraint

$$b^2 - 4ac < 0 , \qquad (14)$$

where a,b,c,d,e,f are coefficients of the ellipse and (x,y) are coordinates of points lying on the ellipse.

The polynomial $F(x,y)$ is called the algebraic distance of the point (x,y) to the given conic.

By introducing vectors

$$\vec{a} = [a,b,c,d,e,f]^T , x = [x^2, xy, y^2, x, y, 1]^T , \qquad (15)$$

it can be rewritten to the vector form as follows:

$$F(x,y) = \vec{x} \cdot \vec{a} . \qquad (16)$$

To prevent the results from fitting to other types of conic not ellipse, an ellipse-specific constraint would be applied.

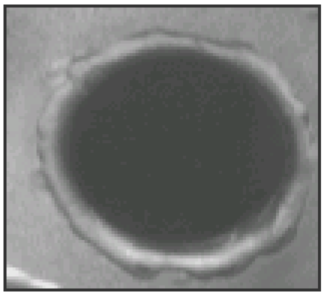
In spite of the advantages in implementation and computing costs of the algebraic ellipse fitting, it has drawbacks in accuracy and the estimated parameters are biased.

Though geometric fitting adopts the euclidean distance as an objective function to address the bias problem, it is based on a time consuming nonlinear least-square fitting.

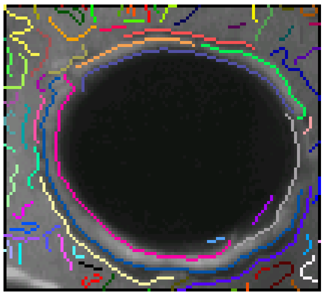
Because the tool position estimation should be taken in a real time manner, computation speed is very important along with robustness. Thus the methods based on the Hough transform or nonlinear least-square fitting are inadequate for the demand of tool position estimation.

To proceed ellipse fitting, edge points of the tube ends are extracted in advance.

Fig.3(b) shows detected edge pixels for a tube end image by using canny's edge detection algorithm. As shown in this figure, the extracted edges represented with several colors are the segmented outliers of the weldment.



(a) Tube end image



(b) Detected edges

Fig. 3 Image of tube end and detected edges

The bias problem arises mainly from fitting only a small section of the ellipse. So it is important to obtain edge points from a larger section of the ellipse if possible. When a large portion of the ellipse boundary is found, it is possible to extract unbiased ellipse with a simple linear least square fitting.

Edge detection method is also crucial because edge points in a large portion of the ellipse are required for unbiased ellipse fitting.

In addition to this, appropriate clustering of the edge points for fitting could result in an unbiased ellipse. Thus only edge points on the same tube ends should be clustered to the same edge group for ellipse fitting.

Too many edge points participating in the ellipse fitting does not improve the accuracy of the estimated parameters so much, but only increases the computation time.

Considering the above observations, edge points for ellipse fitting are collected by searching the edge points starting from an interior point of the ellipse in this paper.

Fig. 4 shows the edge segments $e_1 \sim e_4$ and searching paths (yellow lines) from point P.

Among the edge segments $e_1 \sim e_4$, only e_1 and e_3 are selected for ellipse fitting because these edge segments are encountered several times during edge searching.

The initial point P can be pointed out by human operator during initial setup. Fortunately, the speed of the end effectors is so slow during inspection or plugging tasks that the coordinates of the center points of the tube ends are also slowly varying.

Thus the starting point P can be automatically assigned by the previous center point of the ellipse.

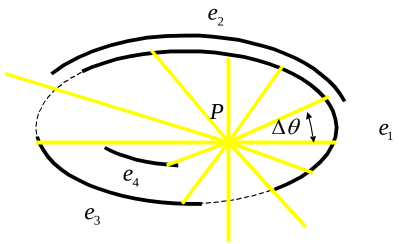


Fig. 4 Selection of edge segments

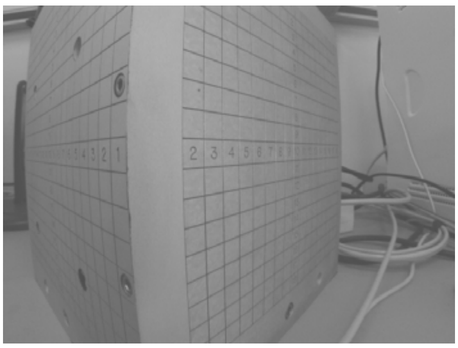
4. EXPERIMENTS AND RESULTS

4.1 Camera Calibration

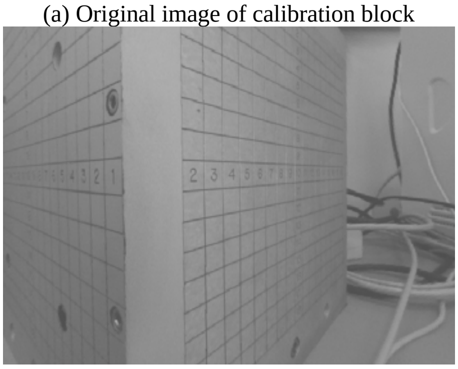
Fig. 5 shows the camera mounted on the ECT inspection probe guide tool. The camera is a PULNIX TM-7CN Monochrome CCD Camera(768 H x 494 V), The lens is a CANON PHF3.5 1.6. 640 x 480 monochrome frame grabber, Matrox Meteo II, is used and installed in the PCI slot of a PC(Pentium IV 2GHZ, 256MB RAM.)

Fig. 5 Camera mounted on inspection tool

The intrinsic camera parameters are calibrated using the calibration block as shown in Fig. 6(a). The distorted image is recovered as shown in Fig. 6(b) using the calibrated intrinsic parameters ($f = 3.65mm, s_X = 1.024, C_X = 327.6, C_Y = 238.5$ $\kappa = 1.77 \times 10^{-2} mm^{-2}$.)



(a) Original image of calibration block

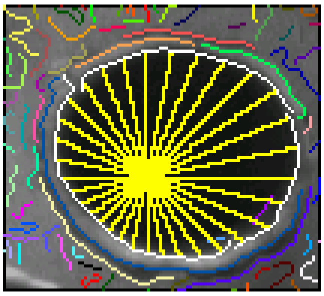


(b) Undistorted image after calibration

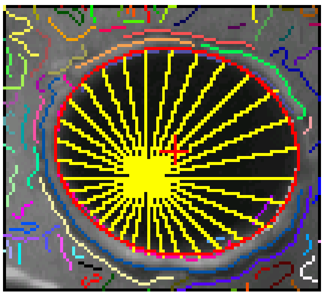
Fig. 6 Results of intrinsic camera calibration

4.2 Ellipse extraction

Fig. 7 shows a ellipse extracted from the image as shown in Fig. 3(a). In Fig. 7(a), white pixels represent the edge segments selected for ellipse fitting. In Fig. 7(b), the ellipse extracted is drawn with a red color and the red-cross mark inside the ellipse represents the center point of the ellipse.



(a) Selected edges for ellipse fitting



(b) Ellipse fitted

Fig. 7 A result of ellipse fitting

4.3 Position and orientation estimation

To estimate the position and orientation of the tool with respect to the tube sheet, ${}^{C}H_{T}$ and ${}^{C}H_{S}$ should be calibrated as shown in Eq. (4). ${}^{C}H_{T}$ is invariant and can be calibrated in advance. Fig. 8 shows the tool calibration plate and calibration points with a yellow crosshair. The message box shown over the image is the extrinsic calibration parameters between the camera and the tool.

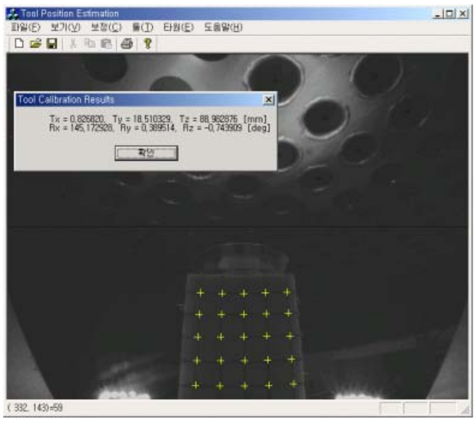
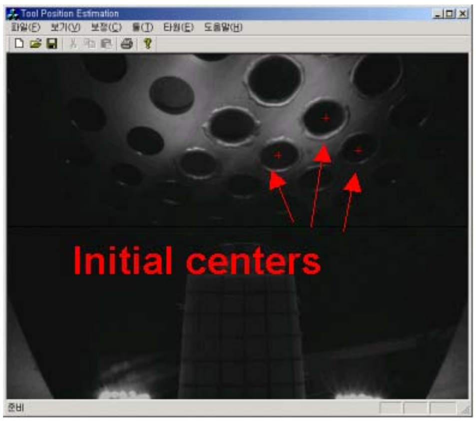


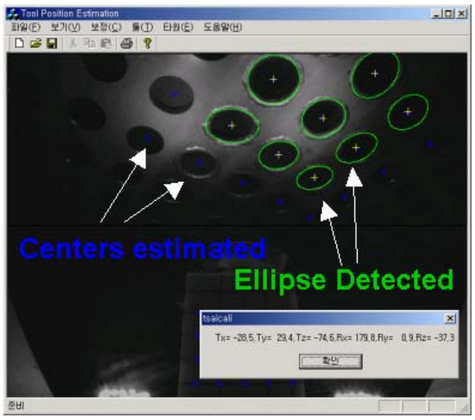
Fig. 8 Tool calibration

After the robot manipulator is installed into the steam generator, a human operator controls the manipulator and selects three points in the image and assigns the coordinates with respect to {S} to each point as mentioned Eq. (1).

Fig. 9(a) shows the three points with a red crosshair marks.



(a) Initial center points assigned by human operator

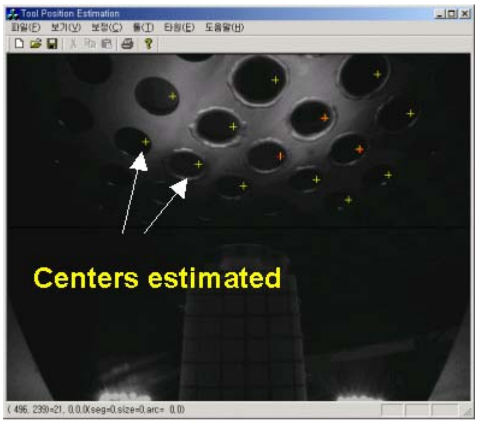


(b) Estimated tool position and orientation

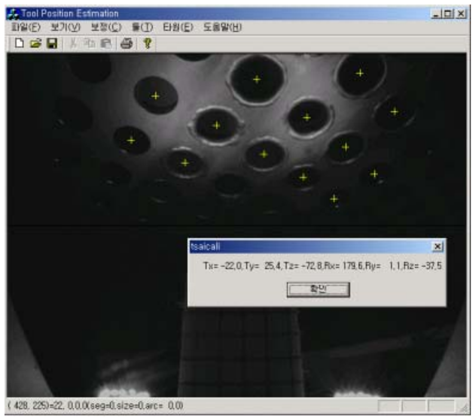
Then the tool estimation system guesses nine initial points including the three points that human the operator has assigned.

Fig. 9(b) shows the detected ellipses in a green color and the message box that contains the position and orientation information of the tool with respect to the tube sheet. Moreover the additional center points that are marked with a blue crosshair are estimated as initial center points for the next step.

After the tool is moved to some extent as shown in Fig. 10(a), the centers estimated in the previous step are used as starting points for the ellipse fitting. In Fig. 10(b), the center points of the detected ellipse are marked with a yellow crosshair and the tool position is displayed in the message box.



(a) Image after tool is moved to some extent



(b)

Fig. 10 Successive estimation of tool position

5. CONCLUSIONS

This paper presents a tool position estimation system for the inspection and maintenance manipulator working inside the steam generator bowl.

By using a general camera calibration approach, tool orientation is also estimated which is crucial in the case of large deflections or robot calibration errors.

To reduce the computation time and avoid the parameter bias problem in ellipse fitting, a small number of edge points were collected around the large section of the ellipse boundary.

In experiments, it was shown that the camera calibration parameters, detected ellipses, and the estimated tool position were appropriate.

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