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A Study on Extraction of the Center Point of Steam Generator Tubes

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Abstract

This paper describes extraction procedures for the center coordinates of steam generator tubes of Youngkwang nuclear power plant No. 6 unit. The centering coordinates of tubes are needed for monitoring whether ECT probe is exactly inserted into tube or not. The centering coordinates extraction procedure consists of two steps. The first step is to process the region with high contrast in entire image of steam generator tubes because the tube image tends not to have uniform contrast in entire image, which resulted from poor illuminations because steam generator bowl is sealed. Using the center points extracted in the first step and the geometry of tubes lined up in regular triangle patterns the centering coordinates of the rest region with low contrast are estimated. The straight lines, that is, from center point of a tube to the other center points of neighboring tubes in the horizontal, 60° and 120° directions are derived using center coordinates extracted only in a high contrast image region. Thus, the intersections of straight lines in horizontal direction and slant lines in regular triangular direction are adopted as the center coordinates of tubes in the rest image region with low contrast. The Chi-square interpolation method is used to determine the line's coefficients. In order to estimate the position and pose of camera assembly camera calibration method is also used. Using tubes geometry that tubes are placed on the tube sheet of steam generator with uniform pitch, 1“ (25.4mm), in the triangular directions, on behalf of calibration chart, the camera calibration is carried out and the extrinsic parameters of camera assembly is estimated.

1. Introduction

The two reactor types PWR and PHWR are normally operated in Korea. A PWR is an acronym derived from the word Pressurized Water Reactor. And PHWR, called CANDU also, is acronym of Pressurized Heavy Water Reactor. The PWR uses water as a moderator and CANDU reactor uses heavy water (Deuterium) as one. The steam generators used in PWR reactor are Westinghouse F (U.S.A.), Framatome 51B (France), and Korean Standard model. In the case of PHWR reactor, AECL CANDU 6 model is used as the steam generator. There are about 3,300 (AECL CANDU 6) to 8,200 (Korean Standard) tubes as the steam generator model. The nominal tube outside diameter of CANDU 6 steam generator tube is 15.875mm

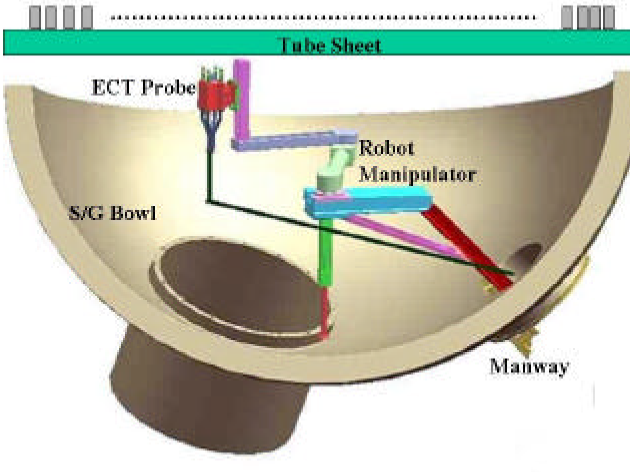
(0.625 in) with a 1.13 mm (0.0445 in) wall thickness and this diameter of Framatome 51B steam generator is 22.225mm (0.875 in) with a 1.27mm (0.05 in) wall thickness. The diameter of the Korean Standard (System 80) steam generator is 19.05mm (0.75 in). [1] The purpose of steam generator tubing is to raise efficiency in heat exchange, installing as many tubes at the same area as possible. Therefore, the inspection and maintenance of steam generator tube in overhaul period is claimed as the safety case for nuclear power plant. It is very important to provide confirming evidence of reliability of the steam generator tube and give assurance that no unforeseen deterioration has taken place. The inspection and maintenance of steam generator tube is in need of remote tooling using robot manipulator system. This is mainly due to:

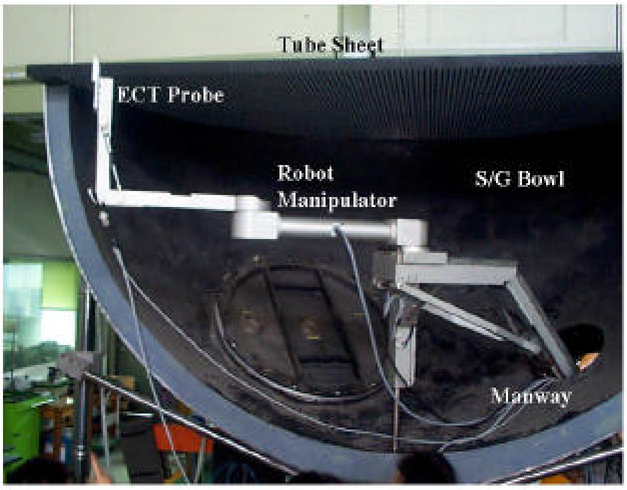
- Increased regulatory requirements
- The radiation dose uptake limits were reduced. (2 rem/year averaged over a 5 years period)
- Inaccessibility

The above factors necessitate the use of robot system within steam generator areas. In general, The ECT (Eddy Current Testing) technique is used to find the flaws of steam generator tubes. The flaws could be a PWSCC (Primary Water Stress Crack Corrosion), denting, pitting, and fretting wear. At the Korea Atomic Energy Research Institute we are developing a robot manipulator for steam generator tube inspection and maintenance. This paper describes extraction procedures for the center coordinates of steam generator tubes of Youngkwang nuclear power plant No. 6 unit. The steam generator of this unit is Korean Standard (System 80) model and tubes are placed in triangular patterns. The centering coordinates of the tubes are needed for monitoring whether the ECT probe is exactly inserted into the tube or not via ECT probe guide assembly. Generally, The tube sheet camera assembly is used to watch any plugging operation in progress in steam generator and monitor the positions of the robot manipulator arm, leg and any associated cabling/hoses or tools. However, tube images acquired by this camera assembly with low light capability and wide FOV lens tend not to have uniform contrast in entire image, which resulted from poor illuminations because steam generator bowl is sealed. The centering coordinates extraction procedure consists of two steps. The first step is to process the region with superior contrast in entire image of steam generator tubes and to extract center points. The center coordinates of the tube image are extracted as following 4 feature methods, which are box, center of gravity, circle, and ellipse fitting. Using the center points extracted in the first step and the geometry of tubes lined up in regular triangle patterns the centering coordinates of the rest region with low contrast are estimated. The straight lines, that is, from center point of a tube to neighboring points in the horizontal, 60° and 120° directions are derived using center coordinates extracted only in superior image region. And then the intersections of straight lines in a horizontal direction and slant lines in regular triangular direction are chosen as the center coordinates of tubes in the rest image region with low contrast. The Chi-square interpolation method is used to determine the line's coefficients. In order to estimate the position and pose of camera assembly camera calibration method is used. In this paper, Using tubes geometry that tubes are placed on the tube sheet of steam generator with uniform pitch, 1“ (25.4mm), in the triangular directions, on behalf of calibration chart, the camera calibration is carried out and the extrinsic parameters, rotation angle and translation vector, of camera assembly is estimated.

2. Steam Generator Maintenance Robot

At the Korea Atomic Energy Research Institute we are developing a robot manipulator for steam generator tube inspection and maintenance. [2] Figure 1 shows the graphic scheme for this tube inspection using ECT method. The robot manipulator under development is targeted for applications of Wooljin 3&4 unit. The Wooljin 3&4 nuclear power plant unit use System 80 steam generator, named Korean Standard, with approximately 8,200 tubes.





(a) Graphic Model (b) Photo of robot manipulator installed in mockup.

Fig. 1. Scheme of ECT Inspection Robot Manipulator

Figure 1(b) illustrates photos of robot manipulator prototype installed in steam generator (Westinghouse F model) mockup. In order to insert the ECT probe into tube smoothly and accurately, it is needed to maintain robot arm and tube sheet in parallel as shown in figure 1(b). Figure 2 shows the tube geometry of Korean Standard (System 80) steam generator used in Wooljin unit 3&4. Tubes are placed on the tube sheet of steam generator with uniform pitch in the triangular directions The pitch between tubes is 1”(25.4 mm) and the outside diameter is 0.75” (19.05mm) with a 0.042” (1.0668 mm) wall thickness. For the robot manipulator installation the operator makes use of a TV monitor, which depicts a side view of the tube sheet or all motions of this robot manipulator made in steam generator bowl. The additional information used for robot manipulator motion is the tool camera (see figure 1-(b)), which is placed on the ECT probe position to monitor the probe in/out process into the tube and the row/column position of the tube being tested. The detailed technical specifications of the steam generators are shown in Table 1.

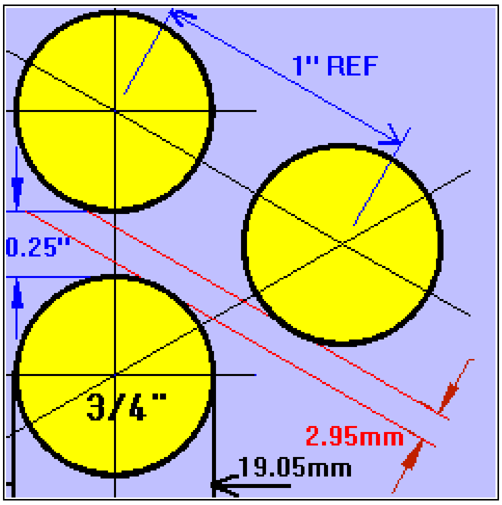


Fig. 2. The geometry of tube placement (System 80)

Table 1. Specification of steam generators

Parameter	Nuclear Power Plant				
	Kori 1	Kori 2,3,4 Young-Kwang 3,4	Wooljin 1,2	Young-Kwang 3,4,5,6 Wooljin 3,4	Wolsung 1,2,3,4
S/G Type	W/H Delta 60	W/H F	F/T 51B	System 80	CANDU 6
Tube Number	4934	5626	3330	8214	3530
Tubing Pattern	Tri	Square	Square	Tri	Tri
Tube Pitch	1.1”	0.98”	1.28”	1.00”	0.95”
Tube Diameter.	0.75”	0.688”	0.875”	0.75”	0.625”
Wall Thickness	0.044”	0.040”	0.05”	0.042”	0.0445”
Material	Inconel 690TT	Inconel 600TT	Inconel 600TT	Inconel 600	Incoloy 800

W/H : Westinghouse (USA), F/T : Framatome (France), Tri : Triangular

In this paper, using the top view image of the tube sheet acquired in the robot manipulator install process, the center points are extracted to estimate parallel error between tube sheet and robot manipulator arm.

3. Camera Calibration

The relative orientation of robot manipulator on the tube sheet could be estimated on assumption that tool camera pose on the same sheet was known. The tool camera pose information can be obtained using camera calibration. The pose information includes intrinsic (focal length, principal point) and extrinsic parameters (rotation and translation). Camera calibration in the context of 3-D machine vision is the process of determining the internal camera geometric, intrinsic parameters, and the 3-D position and orientation of the camera frame relative to a world coordinates system, extrinsic parameters. [3][4] In this paper, we used Tsai's proposed calibration algorithm. The procedure for camera calibration is to use calibration chart, shown in Figure 3. The fiducial marks of calibration chart are created by impressing a template of instant lettering graphics sheet containing many black squares on the top surface of acryl block. All the fiducial marks are placed on a plane with uniform interval, lc, in the horizontal and vertical directions. The calibration procedure is to solve the (1) rigid body transform, (2) perspective relation, and (3) radial lens distortion.

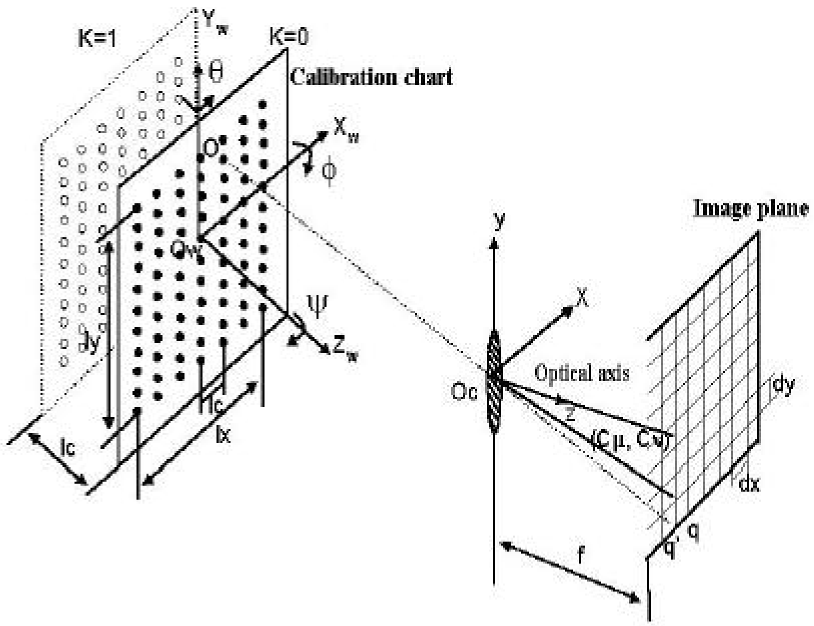


Fig. 3. Setup of calibration chart

$$X_C = RX_W + T \quad (1)$$

In formula (4), X_C and X_W are the vectors of 3-D camera coordinates and 3-D world coordinates respectively. R is the 3X3 rotation matrix and T is the translation vector. The rotation matrix R can be expressed as function of yaw q , pitch f , and tilt y as follows.

$$R = \begin{bmatrix} \mathrm{r1} & \mathrm{r2} & \mathrm{r3} \\ \mathrm{r4} & \mathrm{r5} & \mathrm{r6} \\ \mathrm{r7} & \mathrm{r8} & \mathrm{r9} \end{bmatrix} \quad (2)$$

$$T = \begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix} \quad (3)$$

Where,

$$\begin{aligned}
\mathrm{r1} &= \cos\psi\cos\theta \\
\mathrm{r2} &= \sin\psi\cos\theta \\
\mathrm{r3} &= -\sin\theta \\
\mathrm{r4} &= -\sin\psi\cos\theta + \cos\psi\sin\theta\cos\phi \\
\mathrm{r5} &= \cos\psi\cos\phi + -\sin\psi\sin\theta\sin\phi \\
\mathrm{r6} &= \cos\theta\sin\phi \\
\mathrm{r7} &= \sin\psi\sin\theta + \cos\psi\sin\theta\cos\phi \\
\mathrm{r8} &= -\cos\phi\sin\theta + \sin\psi\sin\theta\cos\phi \\
\mathrm{r9} &= \cos\theta\cos\phi
\end{aligned} \quad (4)$$

However, in the steam generator bowl it is difficult to carry out camera calibration procedure using calibration chart because of restricted access to high radioactivity area such as this bowl. In this paper, we used a circular pattern of tubes placed on the tube sheet of the steam generator with uniform interval, 1”(25.4mm), in the triangular directions (0°, 60° and 120°), on behalf of calibration plate as shown in figure 2. We can estimate the 3-D world coordinates, X_W, from tube layout pattern placed in regular pitch, 25.4mm, in 0°, 60° and 120° directions. The 3-D camera coordinates, X_C, can be replaced by the center coordinates of tubes shaped in circle.

4. Experiment and Results

Figure 4 shows the tube images of System 80 (Korean Standard) steam generator of Youngkwang nuclear power plant 6 under being constructed. The tube image, shown in figure 4, was acquired with a Sony DCR-PC5 digital camcoder, which consists of 1/4" CCD sensor, 10X zoom lens and built-in lamp.

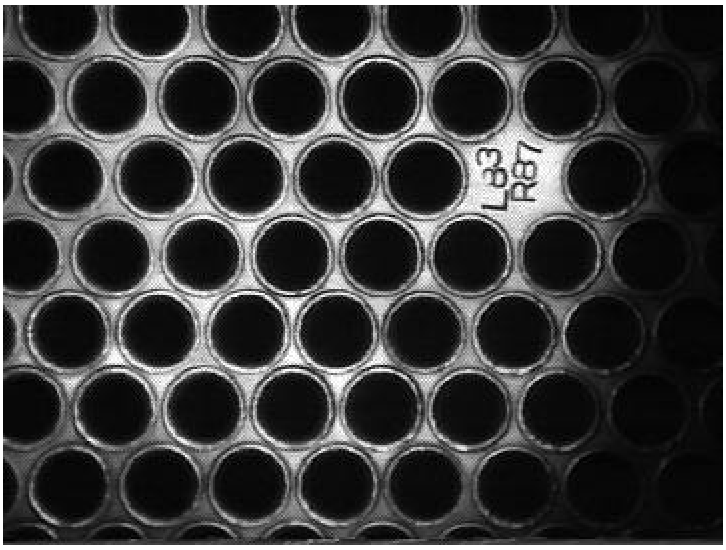


Fig. 4. Tube image of the steam generator (Youngkwang unit 6)

As shown in figure 4, gray level profile in horizontal and vertical directions is not uniform because of low light lamp built in DCR-PC5 camera. The landmark character in the figure 4, L83R87, is the template for operator to identify the row/column positions being tested. The image coordinates, X_C, were extracted as follows.

1) Acquire and smooth a gray scale image.

2) Threshold the image to produce a binary image. The threshold value was set by analysis of intensity histograms, profiles, and projection method. The threshold value to segment circular tube pattern and background critically could not be found over the entire image region (see figure 5).

3) Carry out connectivity analysis via labeling operation. The segmentation is not complete yet. From the point of view of human observer, the binary image shown in figure 5 already consists of many distinct and connected regions. However, the computer sees only an array of zeros and ones and it does not know anything about their neighbors. Thus, region orientated segmentation, which gathers neighboring pixels of the same label and assigns a mark to them, is required.

4) Extracts contours of each label using the gradient operation.

5) Eliminates the non-circular pattern using the aspect, which defined the difference between the major axis and the minor axis of the contour. In case of a circle, the aspect value is 0. It increases if the contour becomes closer to ellipse.

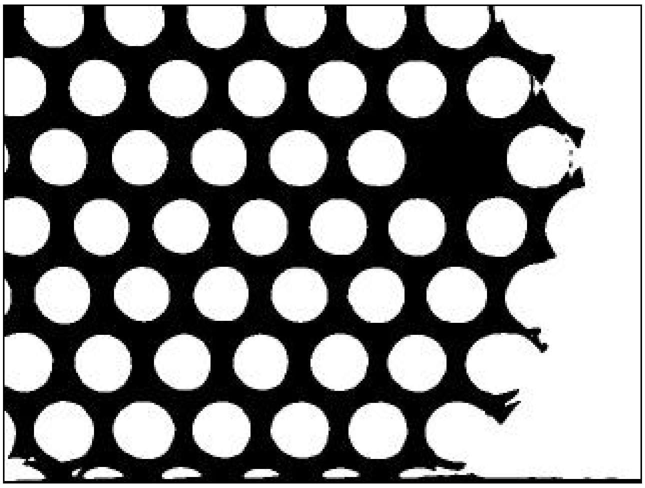


Figure 5. Thresholded binary image of tube

6) Calculates the center points of the contour. In this paper we found the center coordinates of the contour as following 5 feature extraction methods, which are box, box1, center of gravity, circle, and ellipse fitting. The box consists of the coordinates of the extreme left, top, right, and bottom pixels, respectively, of a contour as shown in figure 6. [5]

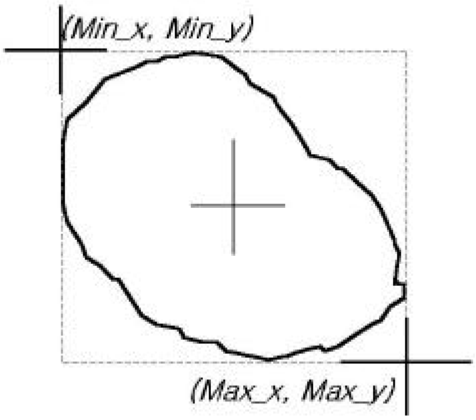


Figure 6. A Box element extraction of the contour

$$Center\_x = Min\_x + \frac{Max\_x - Min\_x}{2}$$

$$Center\_y = Min\_y + \frac{Max\_y - Min\_y}{2} \quad (5)$$

The another box, named box1, consists of the coordinates of the extreme left at top, the top at right, the right at bottom, and the bottom at left pixels, respectively, of a contour as shown in figure 7. These values, together with the above four box1 coordinates, give four contact points on the convex perimeter of the object. In the case of perfect circle, the center coordinates of the box and box1 are the same.

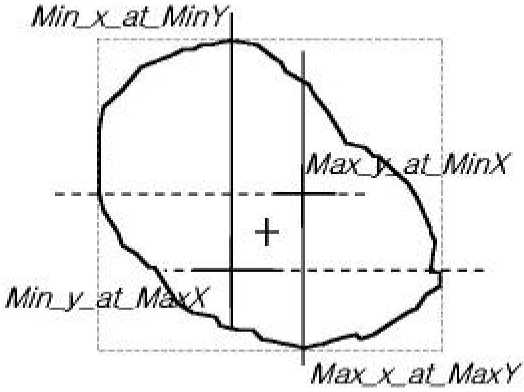


Figure 7. A Box1 element extraction of the contour

$$Center\_x = Min\_x\_at\_Miny + \frac{Max\_x\_at\_MaxY - Min\_x\_at\_Miny}{2}$$

$$Center\_y = Min\_y\_at\_MaxX + \frac{Max\_y\_at\_Minx - Min\_y\_at\_MaxX}{2} \qquad (6)$$

The center of the area is the center of mass of figure of the same shape with constant mass per unit area. (see figure 8) The position of the center of area is as follows. [6]

$$Center\_x = \frac{\iint_I xb(x,y)dxdy}{\iint_I b(x,y)dxdy} \qquad Center\_y = \frac{\iint_I yb(x,y)dxdy}{\iint_I b(x,y)dxdy} \qquad (7)$$

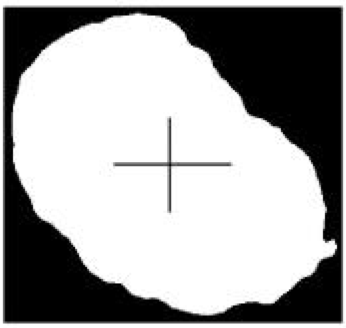


Figure 8. The center of area of the contour region

An ellipse can be described by an equation of the form (see figure 9). [7][8]

$$x^2/a^2 + y^2/b^2 = 1 \tag{8}$$

Where *a* and *b* are the lengths of the semi-axes of the ellipse in the *x* and *y* directions, respectively. If we define

$$f_{ab}(x, y) = 1 - x^2/a^2 - y^2/b^2 \tag{9}$$

we can find the values of a and b which minimize

$$c^2 = \Sigma\left[f_{ab}(x_i, y_i)\right]^2 \tag{10}$$

By setting the partial derivatives of c^2 with respect to a and b to zero, it can be shown that the a and b which minimize c^2 solve the system of two simultaneous equations

$$(\Sigma x_i^2)a^2b^2 - (\Sigma x_i^2 y_i^2)a^2 - (\Sigma x_i^4)b^2 = 0$$

$$(\Sigma y_i^2)a^2b^2 - (\Sigma y_i^4)a^2 - (\Sigma x_i^2 y_i^2)b^2 = 0 \tag{11}$$

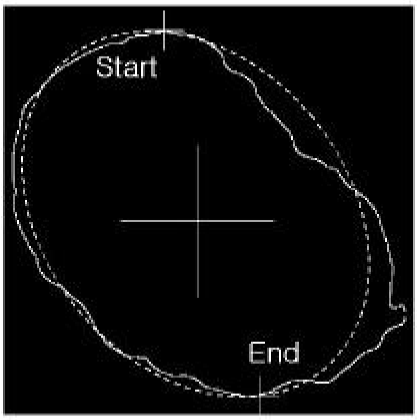


Figure 9. The ellipse-fitting method to find the center of the contour

Figure 10 shows center coordinates of the contour using the ellipse-fitting method among the five feature extraction algorithms.

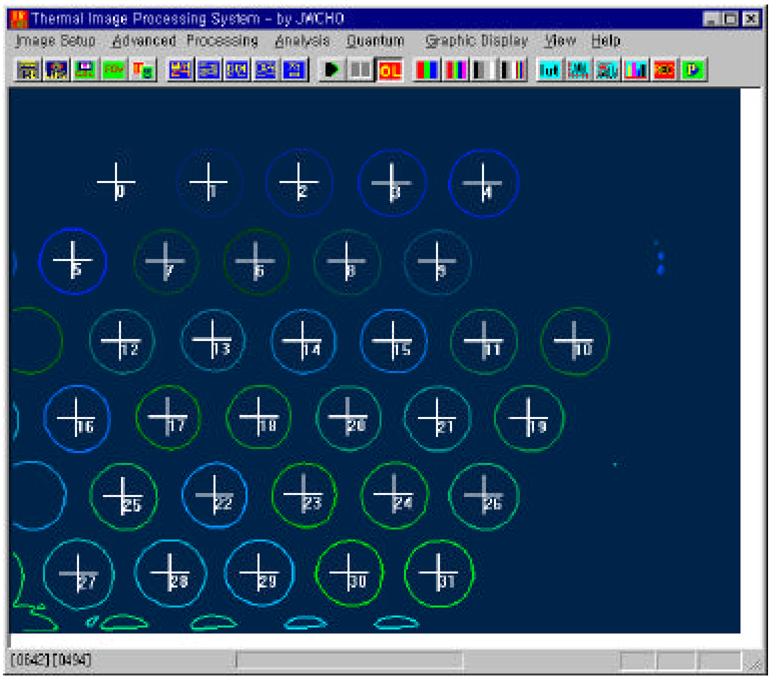


Figure 10. Center coordinates of the contour

7) Fit the straight lines, that is, from the center point of a tube to neighboring points in the horizontal, 60°, and 120° directions using center coordinates extracted only in image region with high contrast as shown in figure 11.

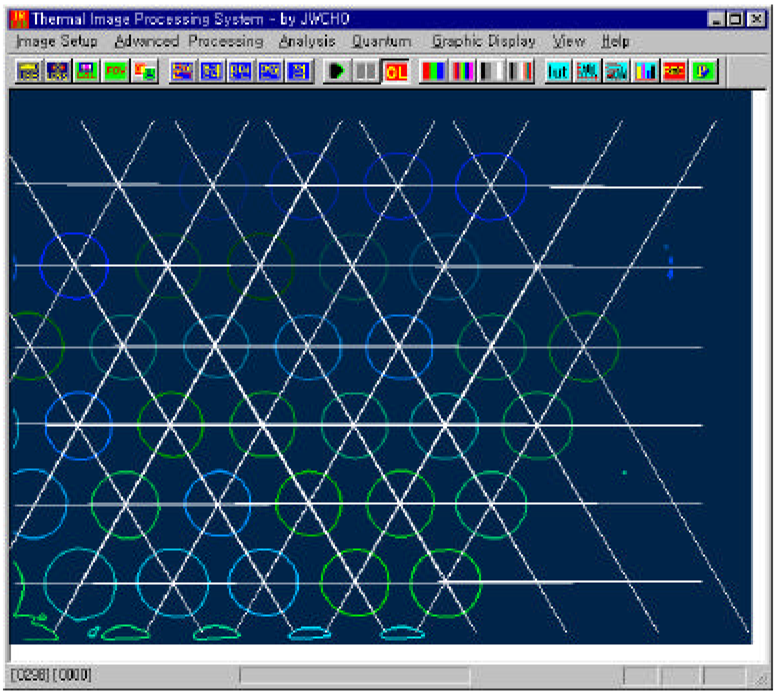


Figure 11. Link center points to derive a set of lines

8) Find the intersections of straight lines in horizontal direction and slant lines in regular triangular direction. The intersection points are the center coordinates of tubes in the rest image region with low contrast (see figure 12)

9) Solves equation (1) using camera coordinates, X_c, extracted the above sequences and 3-D world coordinates, X_w, expressed in tube geometry. (see figure 13).

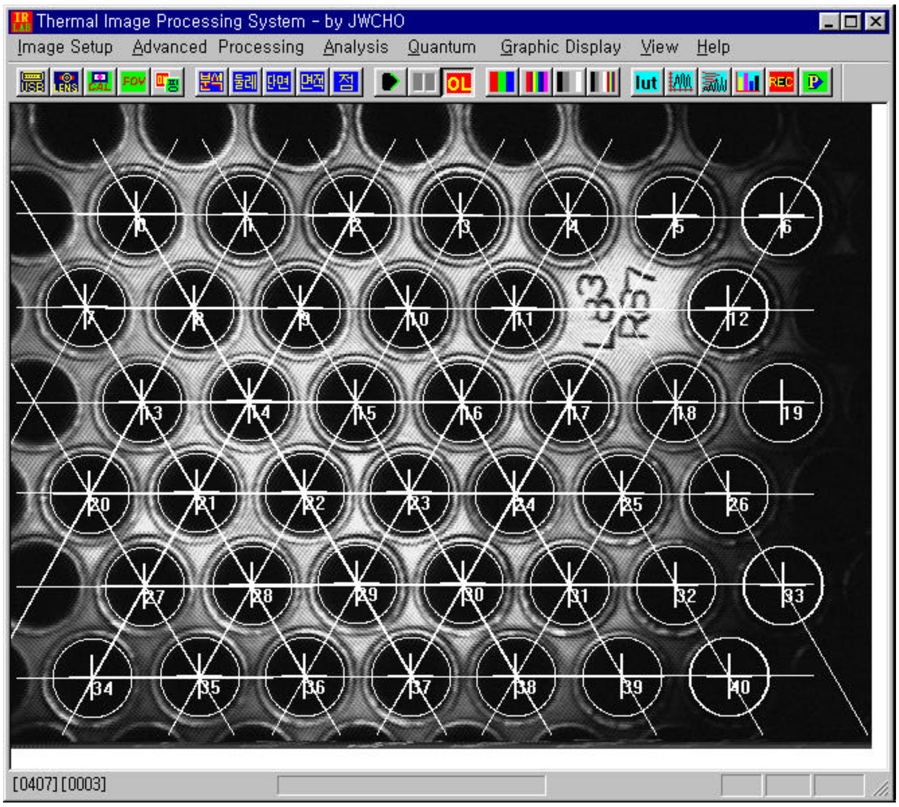
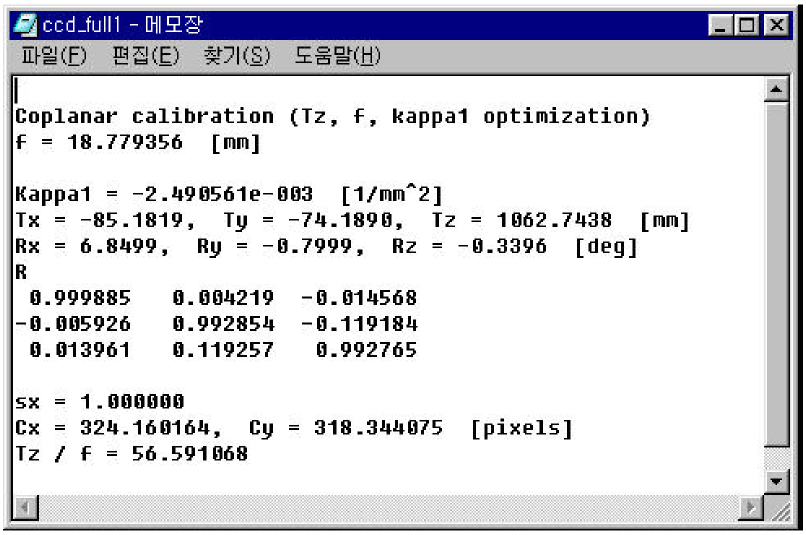


Figure 8. Center coordinates of tube image

We utilize a Matrox Meteor-MC4 frame grabber board, providing for 4-video signal inputs, in an industrial PC rack-mount chassis, with a Pentium host processor card. The software platform is based on Windows 98 operating system and consists of custom native libraries, MIL-LITE 6.1, for image capture, digitizing, memory transfer, and display. Code was written in MSVC6.0 programming language. From figure 9, we know that the line-of-sight distance from camera assembly to tube is 1062.74mm and the focal length is 18.78mm. The calibration results as center points extraction algorithm are shown in table 2. As shown in table 2, focal lengths of the camera assembly are different and variable, from the minimum 17.62mm to the maximum 30.76mm, as center point extraction methods of the tubes. The range, T_z, from camera assembly to tube sheet is also variable as these methods of ones. However, for the experimental results showed in table 2, the ratio of range (T_z) versus focal length (f),

T_z/f, are nearly the same irrespective of center point extraction methods. Assumed that either the focal length of camera assembly or the range from camera assembly to tube sheet was known, in such a restricted case the average error is about 6.8mm with a distance of 1m. From this fact, we conclude that orientation of camera assembly could be calibrated not using any calibration plate but tube geometry if the circular patterns of tubes should be separated from the background completely.




```
Coplanar calibration (Tz, f, kappa1 optimization)
f = 18.779356  [mm]

Kappa1 = -2.490561e-003  [1/mm^2]
Tx = -85.1819,  Ty = -74.1890,  Tz = 1062.7438  [mm]
Rx = 6.8499,  Ry = -0.7999,  Rz = -0.3396  [deg]
R
 0.999885   0.004219  -0.014568
-0.005926   0.992854  -0.119184
 0.013961   0.119257   0.992765

sx = 1.000000
Cx = 324.160164,  Cy = 318.344075  [pixels]
Tz / f = 56.591068
```

Figure 9. Camera calibration

Table 2. Comparison of Center Coordinates Extraction Method

Methods	Tz/f	f [mm]	Center Points		Tz[mm]
Centroid	56.73	17.62	370.15	326.56	999.52
Box	56.57	28.85	596.27	619.40	1632.03
Box1	56.59	18.78	324.16	318.34	1062.74
Ellipse Fitting	56.96	30.76	420.72	331.63	1752.07
Circle Fitting	56.90	21.53	411.87	315.47	1225.33

5. Conclusions

In this paper extraction procedures for the center coordinates of steam generator tubes are described. And these procedures are applied to Youngkwang nuclear power plant No. 6 unit.

The centering coordinates extraction procedure consists of two steps. The first step is to process the region with high contrast in entire image of steam generator tubes. Using the center points extracted in the first step and the geometry of tubes lined up in regular triangle patterns the centering coordinates of the rest region with a low contrast are estimated. The straight lines, that is, from center point of a tube to the other center points of the neighbor tubes in the horizontal, 60° and 120° directions are derived using center coordinates extracted only in high contrast image region. Thus, the intersections of straight lines in horizontal direction and slant lines in regular triangular direction are the center coordinates of tubes in the rest image region with low contrast. The chi-square interpolation method is used to determine the line's coefficients. In order to estimate the position and pose of camera assembly camera calibration method is also used. Using tubes geometry that tubes are placed on the tube sheet of steam generator with uniform pitch, 1" (25.4mm), in the triangular directions, on behalf of calibration chart, the camera calibration is executed and the extrinsic parameters of camera assembly is estimated. Assumed that either the focal length of camera assembly or the range from camera assembly to tube sheet was known, in such a restricted case the average error is about 6.8mm with a distance of 1m. From this fact, we conclude that orientation of camera assembly could be calibrated not using any calibration plate but tube geometry if the circular patterns of tubes should be separated from the background completely.

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