

Design and Development a Software for Wear Measurement of Control Rod Guide Card Based on Machine Vision

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Abstract. The control rod guide tube (CRGT) is used to protect the rod cluster control assembly (RCCA) from bending while providing guidance for the up and down movement of the RCCA. This ensures that the dropping time of the RCCA meets nuclear safety requirements and stops nuclear reactions within the specified time frame. During the up and down movement of the RCCA, the control rod guide cards (CRGC) may experience axial and vibration wear. If the wear is severe, the CRGC may lose its guiding function, resulting in serious problems such as delayed dropping time. In this paper, a machine vision method is proposed to measure the dimensions of the CRGC. Edge extraction, image rectification, and template matching are used to realize autonomous measurement of the CRGC based on its features. The developed measurement software has been used 5 times in domestic nuclear power plant overhauls and has detected 15 CRGTs that were close to the wear limit. This provided data support for the replacement of the CRGTs and effectively improved the quality of nuclear power operation.

1 Preface

The reactor pressure vessel internal component are one of the key components of the pressurized water reactor in a nuclear power plant. These components endure an environment that is continuously influenced by a joint action of elevated temperatures, high pressures, strong radiation exposure, significant thermal loads, and vibrational loads, thereby posing multiple failure risks including stress corrosion cracking under high radiation conditions, wear due to alternating loads, and stress corrosion cracking, among other potential issues.

The internal component is composed of two parts, upper and lower internals, where the upper internals mainly include the upper support plate, control rod guide tubes, support columns, and upper core plates, among other structures. The control rod guide tubes are one of the critical components in the upper internals, serving to provide positioning, guidance, and protection for the movement of the control rod assemblies both upward and downward. They also ensure that the drop time of the control rods meets relevant nuclear safety requirements, thereby enabling rapid control of reactor power output and implementation of emergency shutdowns. The control rod guide tubes consist of two sections, upper and lower guide tubes. Inside these guide tubes, there are 10 layers of CRGC and 1 layer of continuous guiding components that serve to guide the control rods. Over extended periods of operation, due to sliding friction and axial vibrations, wear can occur at locations such as the inner bores of the continuous guiding components, and their connecting ligament. This wear may lead to deviations in the drop time of the control rods, potentially resulting in serious incidents like excessive drop times or even stuck control rods.

According to operational feedback from French nuclear power stations over the past few years, several units have encountered instances of wear on CRGC, with the problem of increased drop times for control rod cluster assemblies potentially being caused by such wear on the bores and their contiguous sections. This wear leads to a bonding effect between the control rod cluster assemblies, thus contributing to longer drop times.

2 CRGT

The control rod guide tube is a tubular structure fixed onto the guide tube support plate. It consists of two sections: an upper guide tube and a lower guide tube, which are respectively located on the upper and lower sides of the guide tube support plate. These two components are joined together tightly by means of a securing flange and bolted onto the guide tube support plate to prevent any loosening during nuclear power plant operation.

The upper control rod guide tube comprises multiple layers of upper guide cards, which are sealed at the top by a cover plate, with a central opening at the top to allow cooling fluid to enter from above and flow along the interior of the control rod. The lower structure of the control rod guide tube includes multiple layers of guide cards as well as a continuous segment assembly. This continuous segment is composed of liner tubes and groove-type tubes, serving to protect the control rod.

The guidance unit is made up of guide holes in the guide card and guide slots in the continuous segment assembly, which ensure that the star-like finger configuration of the control rod cluster can slide through without hindrance. The guide card features 24 guide

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holes, each of which aligns with one of the 24 control rods.

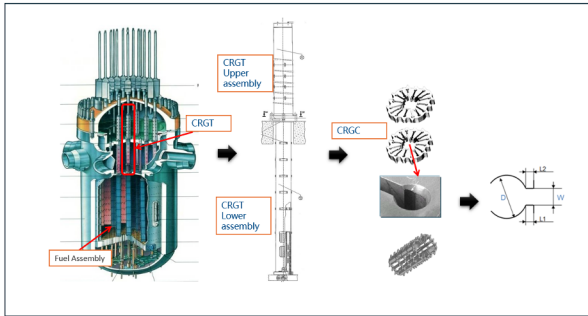


Fig 1. Schematic Diagram of Control Rod Guide Tube Structure

3 Dimensional measurement based on machine vision technology

Machine vision refers to a technology that automatically receives and processes images of real-world objects through optical devices and non-contact sensors, either to acquire desired information or to control robotic motion. The fundamental principle involves converting the observed target into a digital image, followed by processing this image data using specialized software based on its pixel information such as brightness, color, and distribution patterns. According to the processed results, the software can automatically determine the position, dimensions, and appearance characteristics of the product, comparing them against predefined standards to make judgments and provide the outcome of those assessments.

Machine vision systems primarily have four major functions:

- Measurement function
- Inspection function
- Positioning and guidance function
- Recognition function.

Among these, the automatic measurement function can automatically measure the external dimensions of an object, such as its outline profile, aperture size, height, and area, which is applicable in scenarios like measuring the wear amount of control rod guide card assemblies.

4 Design and Development of Measurement Software

4.1 Software Architecture

This software system can be logically divided into three layers: the device layer, data layer, and interface control layer. The device layer is responsible for executing instruction sets related to mechanical movements and security measures. The data layer stores the most fundamental raw data of the entire system, such as collected measurement images, motion configuration parameters, camera setup parameters, report templates, etc. The interface control layer serves as the user interface, implementing operational and display interfaces for various functions. These layers work synchronously and interact with each other through

interfaces, enabling effective information exchange. This design results in strong system expandability, allowing for rapid expansion of new functionalities based on changes in application scale and functional requirements.

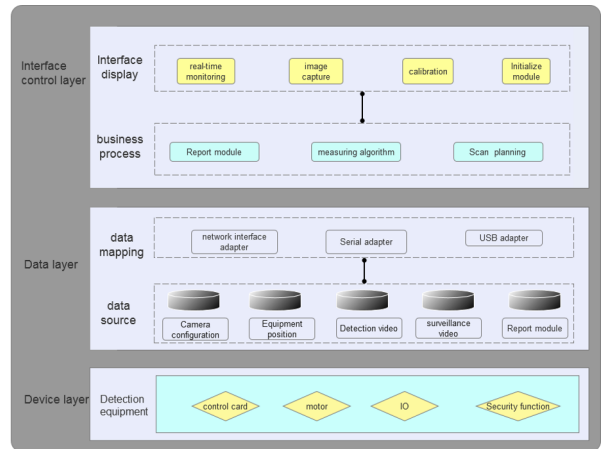


Fig 2. Measurement Software Architecture Diagram

4.2 Software Functional Flowchart

The primary functionality of the measurement software involves preprocessing captured images and extracting outlines from target regions to conduct dimension measurements, with the added feature of automatically saving these measurement outcomes to serve as the underlying data for future data reference and report exportation. The software utilizes object-oriented programming methodologies and follows a modular design philosophy in its functional development.

The system primarily consists of an image capture module, a calibration module, an image processing module, a motion control module, a reporting module, and a data management module.

The software functionality diagram is illustrated in Fig3. Among them, the image processing module is the core component of the measurement software, employing the Sobel edge detection filter, a chessboard correction tool, and automated measurement algorithms to carry out accurate dimensional measurements of guide cards.

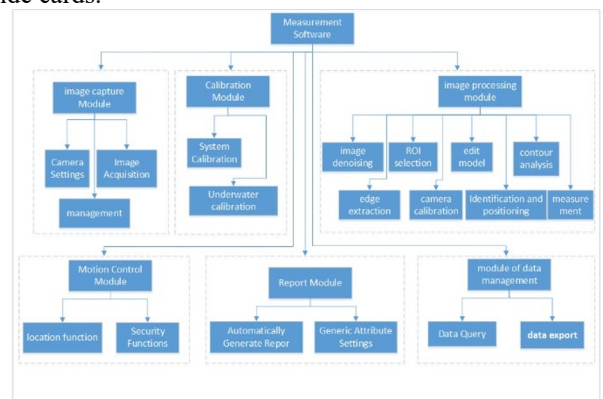


Fig 3. Functional diagram of measurement software system

The image acquisition module utilizes an image acquisition card to store images in a collection database

for subsequent analysis; the calibration submodule encompasses both the calibration of the motion system and the verification of underwater measurement precision.

The Main Functions of the Motion Control Module are as follows:

- 1) Menu Bar: Houses options such as software exit and mechanical backlash compensation settings.
- 2) Connection Setup: Facilitates connections to the Input/Output (IO) controller and the ELMO GMAS controller.
- 3) Hoist Hook Control: Manages the cylinder lock mechanism for the hoist hook, enabling control over its engagement/disengagement.
- 4) Inclinometer Function: Monitors and displays the vertical orientation status of the equipment itself.
- 5) Axial Movement Control: Regulates the vertical linear motion along the axis of the device.
- 6) Radial Movement Control: Directs the rotational movement of the device around its axis.
- 7) Camera and Lighting Control: Controls the extension and retraction of the camera, as well as the operation of the camera lights.
- 8) Camera Position Information: Provides real-time information on the current position of the camera within the guide card array.
- 9) Status and Prompt Messages: Displays current operational information and prompts to guide the user during the operation process.

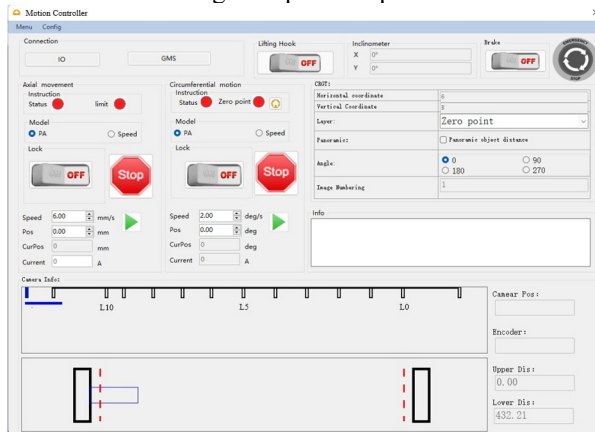


Fig 4. Motion Control Module Page

4.3 Image Processing Module

VisionPro is an advanced visual software development platform. It is primarily used for setting up and deploying vision application systems based on cameras or image acquisition cards. Leveraging secondary development with VisionPro, functionalities such as dimensional measurement of workpieces, positioning navigation of moving mechanisms, and text recognition can be realized.

The acquired images need to undergo preprocessing, which includes operations such as threshold segmentation, image denoising, edge extraction, and image correction, to enhance the accuracy of image

contour recognition. After the contour is extracted, automatic dimension measurement needs to be performed based on the recognized features.

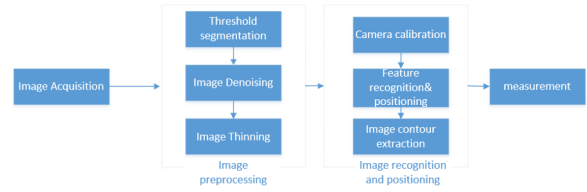


Fig 5. Image processing and analysis workflow

4.3.1 Edge Detection

The Sobel([1]) filter calculates the grayscale weighted difference between the pixels in the eight adjacent positions above, below, left, and right of a certain pixel in the image. It detects the phenomenon where the calculated value reaches an extreme value at the edge to detect edges. This operator has a good smoothing effect on noise and provides more accurate edge direction information. The Sobel filter uses two 3×3 kernels for calculation. One is used to detect pixel changes in the horizontal direction, and the other is used to detect pixel changes in the vertical direction. The two kernels are convolved with the original image to calculate the approximate values of the derivatives. G_x and G_y are the approximate values of the vertical derivatives and horizontal derivatives, respectively. The calculation formula is as follows:

$$G_x = \begin{pmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{pmatrix} * A \quad (1)$$

$$G_y = \begin{pmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{pmatrix} * A \quad (2)$$

Where A is the grayscale matrix of the original source image, and the X-coordinate is defined to increase in the horizontal rightward direction, with the Y-coordinate being defined to increase in the vertical downward.

For every pixel in the image, the gradient magnitude is computed by applying the following formula that considers the gradients in both the x and y dimensions.

$$G = \sqrt{G_x^2 + G_y^2} \quad (3)$$

$$\theta = \arctan\left(\frac{G_x}{G_y}\right) \quad (4)$$

Use formula 4 to calculate the direction of the gradient. If the gradient G at a particular point exceeds the designated threshold value, it is deemed to be an edge point; otherwise, proceed to compute the gradient value and gradient orientation of the subsequent point.

The result of edge detection using the Sobel filter is shown on the right side of the figure, where the edges of the image have been significantly enhanced

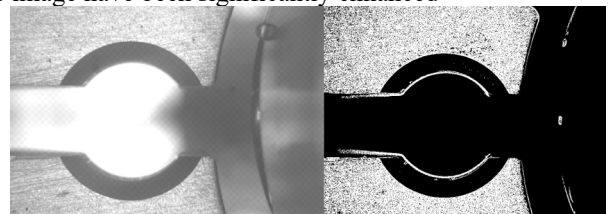


Fig 6. Edge Detection Based on Sobel Operator

4.3.2 Camera Distortion and Calibration

Due to the shape of the lens, radial distortion is introduced, and in the camera assembly process, since it's not guaranteed that the lens is strictly parallel to the imaging plane, tangential distortion is also introduced.

For a certain corner point(p_1) on the chessboard, we first assume that its pixel coordinates are obtained through a corner detection algorithm(x_1, y_1). Then, using a well-calibrated camera model, the corner point is reprojected to obtain new pixel coordinate(x_2, y_2). The calibration accuracy of the camera is evaluated by calculating the error between these two sets of pixel coordinates. Finally, the average of all corner point errors is taken to derive the reprojection error for the camera calibration([2-3]), as shown in the formula(5).

$$f_{err} = \frac{\sum_{i=1}^n ((x_1 - x_2)^2 + (y_1 - y_2)^2)^{1/2}}{n} \quad (5)$$

The Check-board tool within the VisionPro platform is used to calibrate the camera, which involves pinpointing the exact values of distortion parameters. Once the camera calibration process is finished, applying those distortion parameters to the acquired images enables the necessary corrections, effectively minimizing radial and tangential distortions in the images and boosting the overall measurement precision.

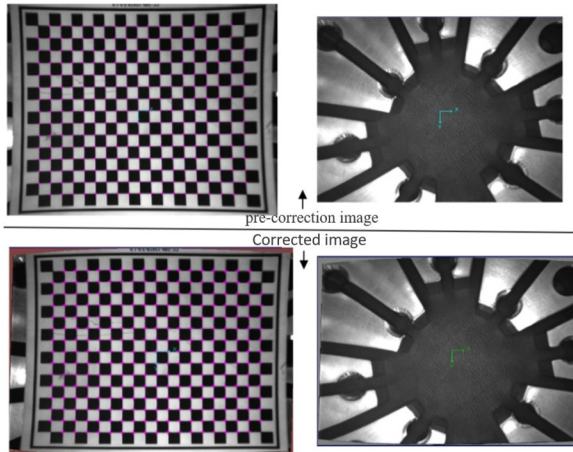


Fig 7. Comparison of Images Before and After Correction

4.3.3 Automatic Measurement Algorithm

Upon acquiring the image outlines via the sequence of image processing techniques, tailored algorithms are devised to compute dimensions at relevant locations. Fig8. illustrates the segments employed for measuring dimensions.

Overview of Dimension Measurement Algorithms:

- 1) Obtain the centre O of the circular hole on the guide card by fitting the contour of the outer circle of the guide card.
- 2) According to the engineering drawing, construct the theoretical upper and lower side lines L1 and L2 for the strap of the guide card, where the line L2 that lies on the same side as the centre O is defined, and it is located below the line L1.

- 3) Fit the contour of the strap and retain only the lower part of the region contour beneath line L2, labelling these sections as W1 and W2.
- 4) Establish a coordinate system with the origin at point O, where the X-axis is a line passing through O and parallel to line L1, with positive direction from left to right. The Y-axis also passes through the origin O and is perpendicular to the X-axis, with positive direction from top to bottom.
- 5) Identify contours and sets of points within the image.
- 6) Calculate the maximum width W between any two points within the identified contour area.

Traversal of the point set (WP_i) for the left contour of the ligament (W1):

{

Traversal of the point set(WP_j) for the right contour of the ligament (W2):

{

Calculate the intersection points between the left and right sides of the ligament and save the pairs of intersection points in a Dictionary (WP_i, WP_z) array.

}

}

Traverse the point pairs in the Dictionary to calculate the maximum width W,

Distance calculation formula between point (WP_i, WP_z):

$$W_{i,z} = \sqrt{(WP_i.X - WP_z.X)^2 + (WP_i.Y - WP_z.Y)^2} \quad (6)$$

Where WP_z is the point WP_i that intersects with point WP_j along a direction parallel to the slot width; $WP_i.X$ represents the X-axis coordinate value of point WP_i in the image coordinate system, $WP_i.Y$ represents the Y-axis coordinate value of point WP_i in the image coordinate system.

$WP_z.X$ represents the X-axis coordinate value of point WP_z in the image coordinate system, and $WP_z.Y$ represents the Y-axis coordinate value of point WP_z in the image coordinate system.

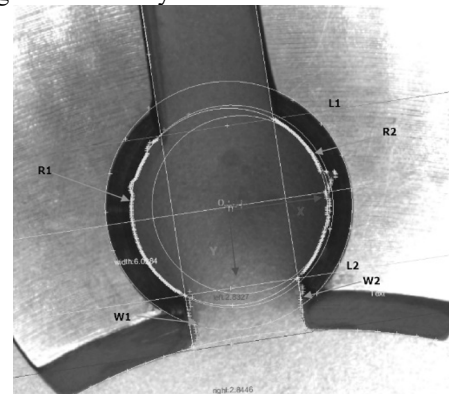


Fig 8. Schematic Diagram of Dimension Calculation Algorithm

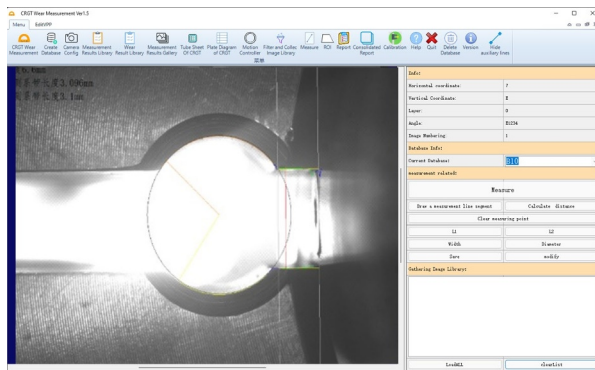


Fig 9. CRGT Wear Measurement Software

5 Test Scheme

In machine vision technology for measuring workpiece dimensions, the choice of parameters like field of view, lenses, and illumination sources can greatly impact the accuracy of the measurement outcomes. Therefore, to attain higher measurement accuracy, various combination strategies have been utilized during actual testing, with each measurement conducted using different setups. Depending on the specific conditions of the inspection environment, it is possible to select the most appropriate configurations for the field of view, lenses, and lighting equipment.



Fig 10. Measurement Scheme Combination Matrix

Taking a ring light as an example, the testing steps using a 176mm fixed-focus lens with a field of view covering one quarter of a guide card are as follows:

- 1) Mount the industrial camera onto the inspection mechanism so that the camera can move axially and rotate circumferentially along with the inspection apparatus.
- 2) Adjust the light source intensity to acquire images with sufficient contrast, select a region from the image that possesses inspection features to create an image template, mark the detection position on it, and save this template.
- 3) Measure the pixel values of the calibration test block and calculate the conversion factor based on the actual dimensions of the calibration block.

- 4) Use software to automatically test the relevant dimensions and subsequently compute the wear amount.

Table 1. Measurement Record (mm).

Index	First Measurement	Second Measurement	Third Measurement	Actual Dimension	Deviation 1	Deviation 2	Deviation 3
D4	10.74	10.5	10.49	10.73	-0.01	0.23	0.24
E1	10.67	10.68	10.68	10.73	0.06	0.05	0.05
B1	10.51	10.50	10.50	10.72	0.21	0.22	0.22
E1_W	6.37	6.33	6.33	6.16	-0.21	-0.17	-0.17
E1_L1	2.88	2.82	2.81	2.95	0.07	0.13	0.14
E1_L2	2.80	2.72	2.70	3.03	0.23	0.31	0.33

Under the optimal test combination, the measurement accuracy of hole diameters is around 0.24mm, and the measurement accuracy of slot width (W) is also approximately 0.21mm. The measurement accuracy of slot lengths (L1, L2) is about 0.33mm.

6 CONCLUSION

Using machine vision technology to measure the wear on guide cards can greatly simplify mechanical structures compared to ultrasonic testing methods and mitigate a range of inspection-related risks at nuclear power plant sites. A measurement software developed according to this approach has been utilized used 5 times in China’s nuclear power plant overhauls, and has identified 15 CRGTs that approached their wear threshold, providing data support for components replacement, contributing to a marked improvement in the operational quality of nuclear power facilities.

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