Automated Analysis of AGR Fuel Channel Inspection Videos

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Abstract

Remote Visual Inspection of the fuel channels which form the reactor cores of the UK’s fleet of Advanced Gas-Cooled Reactors (AGRs) occurs during planned periodic outages and provides station operators with a detailed understanding of core condition. A typical single fuel channel inspection generates a large amount of footage which must be analysed before the station is returned to power (provided it is safe to do so). While manual approaches are currently used, inspection videos can be analysed efficiently using techniques from image processing and computer vision. For example, the ASIST (Automated Software Image Stitching Tool) software processes inspection videos to construct a single image known as a chanorama (channel panorama) which allows the full inside surface of a single fuel channel to be viewed in a snapshot. To accurately characterise defects such as cracks in chanoramas, their dimensions need to be measured. This requires channel features of known size to serve as references to calculate scaling factors. These features vary from station to station and include overall brick dimensions, trepanned holes and keyways. In this paper, we propose a series of algorithms to automatically detect and measure the dimensions of each of these known features. In turn, this information can be used to generate a scaling factor which can be applied when sizing any cracks detected in a given chanorama.

Keywords
Image Processing, Hough Transform, Hit-or-Miss-Transform

INTRODUCTION

The majority of the UK’s nuclear power is currently generated by a fleet of 7 stations of the Advanced Gas-Cooled Reactor (AGR) design. The graphite core of the AGR is one of the major life limiting components of the reactor as it cannot be repaired or replaced. Remote Visual Inspection (RVI) of the fuel channels which form the AGR cores is conducted every 1-3 years to determine the physical health of the core. RVI records video footage of the entire inner walls of a carefully selected subset of fuel channels. Fuel channel inspection is performed using either a Channel Bore Inspection Unit (CBIU) or a New In Core Inspection Equipment Mark 2 (NICIE Mk2) tool specifically designed for this application [1]. Once the video data is acquired, it is analysed by a team of expert inspection engineers who view the footage to locate...
anomalies or defects and manually generate montage images of any defects found. This is a very time consuming process and, for a single, complex crack, can take up to one full working day to complete before the resulting montages are later studied at a Graphite Assessment Panel (GAP) where the cracks are categorized. The station is not producing power while this analysis is being performed and cannot return to power until the inspection is over so it is desirable to minimize the time taken to construct the montages.

Since 2012, Murray et al. [2, 3] have worked with EDF Energy to design and develop a custom piece of software known as ASIST (Automated Software Image Stitching Tool). This software can be used to automatically stitch the video frames recorded during scheduled outages to automatically create panoramic images spanning the complete inner surface of a fuel channel. These images are known as chanoramas (fuel channel panoramas). A full chanorama can be automatically produced in approximately 20-30 minutes which is considerably less time than that required to manually construct a crack montage. In order to accurately size any defects observed, a scaling factor is required to convert pixel measurements to real world metric distances. At present, scaling factors and crack dimension are calculated manually using known physical features within the chanoramas. This paper presents a summary of new image processing algorithms which are being developed to automatically detect these known physical features within the chanorama images and to make pixel accurate measurements of the dimensions of these physical features. We then demonstrate how these techniques may be used to calculate the dimensions of a known channel feature (trepanned hole) and a crack.

Data Acquisition

Each AGR graphite core is comprised of approx. 10 layers of approx. 300 hollow cylindrical graphite bricks (these numbers vary from station to station) which are stacked one on top of another to form large cylindrical columns. These columns, known as fuel channels, provide housing for the fuel and the graphite provides a moderator the nuclear reaction. The RVI footage gathered during inspection consists of video scans of the inside walls of the fuel channels selected for inspection. The footage is recorded using a specialist radiation hardened camera which is mounted on a suitable tool (CBIU or NICIE Mk2) and inserted into a fuel channel under inspection. The camera faces directly down the channel but scans of the inside walls of the channel are made using a mirror mounted on the end of the tool reflecting an image of the side wall into the camera. The camera has a horizontal field of view of approximately 70 degrees and full coverage of the inside wall of the fuel channel is obtained by recording 6 different scans at different orientations at increments of 60 degrees. A more detailed explanation of the inspection process may be found in [2].

ASIST (Automated Software Image Stitching Tool)

The raw video data recorded during inspection consists of down-channel footage and six sequential scans at different orientations with a 70 degree field of view to ensure all the inside of the fuel channel has been imaged. ASIST is a custom piece of software designed and developed by the University of Strathclyde to convert these videos into chanoramas. ASIST achieves this in a number of steps:
1. Decomposes the video into frames
2. Automatically determines the start and stop frames for each scan
3. Stitches the appropriate frames into a single strip for each orientation
4. Calculates overlaps and horizontally stitches each of the strips
5. Any further post processing required before exporting the completed image.

ASIST is capable of working with custom configurations and manual intervention can be made at any step of the process. For a more detailed overview of ASIST see [2]. To date, ASIST has processed over 500 unique inspection videos and generated chanorama images for each of these.

**Defect Sizing**

We present a number of ways to calculate the accurate scaling factors required for measuring the dimensions of defects observed in chanorama images. Scaling factors are required to equate pixel measurements of defects to real world metric distances. Scaling factors can be calculated using known channel dimensions such as brick height, keyway width or trepanned hole dimensions. There are a number of challenges associated with calculating scaling factor using any of these references.

- Different scaling factors are required for horizontal and vertical measurements in chanoramas. This is due to variations in speed of the inspection camera as it moves up through the channel resulting in vertically elongated strips. This effect can be clearly seen by considering the image of a circular trepanned hole as shown in Figure 3(a).
- Different brick layers have different heights in completed chanorama images due to the camera’s vertical movement slowing down as it moves up the channel.
- The width of a keyway as measured in pixels is dependent on its x position in any given frame or any single chanorama strips due to camera and mirror distortions.

The last point presents the greatest challenge to calculating a global scaling factor. Distortions to the image are introduced by the camera and mirror imaging a curved surface. This has been clearly demonstrated using an experimental rig in the University of Strathclyde. The rig consists of three graphite bricks and an EDF Energy inspection camera that is representative of the cameras used in all NICIE/CBIU tools. Figure 1 shows a snapshot of a uniform checkerboard placed flush inside one of the graphite bricks in the rig. It is clear that the squares are significantly larger in width in the extreme left and right of the image when compared to the image centre region. To illustrate this further, Figure 2 shows a plot of the width of each the black square versus x position which quantifies this variation.

![Figure 1: Section of checkerboard imaged using camera and Strathclyde experimental rig.](image-url)
Currently, inspection engineers measure the keyway that is most central in all the chanorama scans and use this as reference to calculate a horizontal scaling factor. This scaling factor is then used for all horizontal measurements. Similarly a vertical scaling factor is calculated using the known brick layer height.

![Black Square Width versus x-Position](image)

*Figure 2: Width of black squares as a function of x position.*

**AUTOMATED REGION OF INTEREST DETECTION**

In this section we demonstrate approaches to automatically localize and make precise pixel measurements of the dimensions of trepanned holes and keyways. We also present a novel method for highlighting any areas in a full chanorama which may contain cracks.

**Automatic Trepanned Hole Detection**

To gain insight into how the graphite changes due to prolonged irradiation in the core, cylindrical samples are extracted and analysed. These samples are extracted from the inner wall of a fuel channel using a specialized trepanning tool [4]. The diameter of the tool is fixed so all trepanned holes which appear in chanorama images have a known and fixed diameter of 23 mm. This provides an ideal standard for calculating a scaling factor. A typical chanorama is over 160 megapixels in size so it is essential to have a very efficient method to automatically detect the trepanned holes in the images. The Hough Transform (HT) adapted for circles is a very suitable tool for this task. The HT was originally proposed for detecting straight lines in images [5] and was later adapted by [6] for the detection of circles and curves. To detect all trepanned holes in any brick layer, the input image (Figure 3(a)) is first converted to a binary image (Figure 3(b)) by thresholding. A binary edge image (Figure 3(c)) is computed by applying an edge detector such as Sobel, Canny, Roberts, Laplacian of Gaussian, or any suitable alternative. The HT is then applied to this binary edge image and any detected circles are returned as a binary mask which can be overlaid on the original image (Figure 3(d)).

While the circle detector is very effective to detect trepanned holes, it is not sufficiently accurate to make measurements of their dimensions. This is due to the holes being elongated into ellipses in the chanoramas. In some cases, such as shown in Figure 3(d), multiple circle detections can occur on a
single trepanned hole. This does not cause any problems for localizing the trepanned hole provided the detections overlap, however, accurate measurements of the dimensions of the trepanned hole cannot be made. To overcome this, we use the HT to detect the location of trepanned holes before applying a localised ellipse detector to accurately measure its dimensions. That is, we detect the centroid of all overlapping HT detections and only consider a small local area when searching for ellipses.

The region around the detected trepanned hole located in Figure 3(d) is then cropped resulting in Figure 3(e), a new binary image Figure 3(f) and edge image Figure 3(g) are computed and the ellipse detector described in [7] is applied to the binary edge image. This approach fits an ellipse by examining all possible major axes (all pairs of points) before computing the minor axis using the Hough Transform. The output of the ellipse detector is a set of 5 parameters (major and minor axes, centre point and orientation) describing the ellipse’s relative position in the input image. This output is plotted on the binary edge image and original image in Figure 3(g) and Figure 3(h) respectively. The reason ellipse detection is not used for the full image is due to the additional parameters required to describe an ellipse resulting in a very large computational overhead.

![Figure 3: Stages of detecting and measuring the size of a trepanned hole.](image)

**Automatic Keyway Detection**

Keys and keyways at the bottom and top of each graphite brick that are used to connect the bricks of each fuel channel together when stacked on top of each other. As keyways have a known shape and size, it is possible to design a template matching algorithm to automatically detect them and use them for scaling. In this section, we outline a suitable multistage approach to automatically detect keyways with each of the steps outlined in Figure 4.
The most fundamental stage in this approach is a transform from Mathematical Morphology known as the Hit-or-Miss Transform (HMT)\[8, 9\]. The HMT is a template matching method which works on a binary images and uses two complementary structuring elements to simultaneously match the foreground and background of a given image. Suitable structuring elements for the foreground and background are given in Figure 5 as the keyways shape is known. The HMT works by searching the image for the foreground template and marking all points where it is contained. The same operation is performed with the background template on the complementary (inverted) image and all locations where the background template is contained are also marked. The output of the HMT contains all regions where these two operations are simultaneously matched as illustrated in Figure 6.
We apply the HMT to a binary image obtained by thresholding the chanorama images and it is advantageous to perform some pre-processing to improve performance. As keyways always occur on a brick layer interface, it is only necessary to search the region below the interface for the keyways. Murray et al. [2] demonstrate an effective technique for automatically detecting brick layer interfaces by performing analysis on the average brightness of each row in a full chanorama.

To detect all the keyways at a brick interface, we start by cropping out a strip containing only the interface and keyways as shown in Figure 4(a). The image is inverted and noise removed using a median filter resulting in Figure 4(b). A binary image is computed by considering a fixed number of the brightest pixels in each column, setting these pixels to 1 and all other pixels in the column to 0 resulting in Figure 4(c). The HMT is then applied to this image resulting in a binary detection mask with the locations of the keyways as shown in Figure 4(d). To improve detection performance, further post processing is applied to the binary detection mask such as a dilation to join smaller detection regions Figure 4(e) and an upper and lower limit on the size of any detection region. These detections are then overlaid on the original image Figure 4(f), and compared to the ground truth Figure 4(g).

This approach can be applied to each brick layer interface and the information summarised in a single image showing all the keyways and interfaces as shown in Figure 7.

![Figure 7: Interface summary image showing all detected keyway pixels.](image)

**Accurately Measuring Keyway Dimensions**

To use a keyway to calculate a scaling factor, the exact pixel width of a keyway must be measured. While the approach outlined previously accurately locates the majority of keyways, the detected objects in the binary detection masks do not cover the full keyway so the keyway dimensions cannot be measured directly. Exact binary detection masks are not required as we only need to measure the keyway widths. This can be achieved using techniques from 1D signal processing. Using each detected object in the binary detection mask as a seed point, we can crop out each keyway and a localized region as shown in Figure 8(a). To find the left and right edge of the keyway we convert the image into a 1D signal by calculating the sum of every pixel in each column. The edges in the keyway will appear as a sudden transition in the 1D signal and this can be detected more easily by removing the low frequency components of the signal using a highpass filter as shown in Figure 8(b). The two largest peaks correspond to the keyway edges and their locations are extracted and plotted in the original keyway image as shown in Figure 8(c). Using the measured width in pixels and the known physical dimensions for keyways in each station allows an accurate horizontal scaling factor to be calculated.
Automatic Crack Detection

It is possible to automatically localize defects such as cracks in full chanoramas using a technique from computer vision and machine learning known as the Bag-of-Visual-Words (BoVW) object detection framework. A comprehensive introduction to machine learning is beyond the scope of the paper but the reader is directed to [10]. BoVW is a technique used to classify an object in any given image into a particular set or class. The problem of determining if an image contains a crack or is uncracked is a binary classification problem requiring a large number of examples (instances) of both cases. In order to create a suitable model to determine which class any given instance belongs in, a training set can be used to train a classifier. This training set consists of image sub-tiles taken from chanoramas which contain both cracks and uncracked regions and accompanying labels. The performance of any classifier must be evaluated on a distinct, unseen, test set which also contains a sufficient number of examples from both classes in order to calculate appropriate performance metrics.

Most classifiers require the input features to be a fixed length vector and, while it would be possible to use fixed dimension images to train a classifier, it would not perform very well and likely not be invariant to rotations or scale. To overcome this, the BoVW approach learns a vocabulary of “visual words” or “phrases” that are representative/characteristic of each class in the problem and usually independent of scale and rotation. The histogram of frequencies of occurrences of each of these visual works provides the fixed length input vector required to train the classifier and also to test new instances. The BoVW object detection framework is usually most successfully applied to smaller images and it would not be practical to train suitable classifiers to operate at the scale of a full chanorama therefore we train it to label small patches as cracked/not cracked. To apply it to a full chanorama a sliding window approach is used to test many overlapping image patches to compute a coarse spatial crack likelihood map. This can be presented to a user by applying a suitable colourmap, resizing and overlaying on the original image as shown in Figure 9. This approach can be applied to a full chanorama as shown in Figure 10. This image serves to rapidly draw a user’s attention to any anomalies such as the two cracked brick layers on the right hand side of the image.
CASE STUDIES

In the previous section we demonstrated techniques suitable to automatically locate and measure keyways and trepanned holes in chanoramas. While keyways are present in 5 of the 7 AGR stations, trepanned holes are only present in a limited subset of fuel channels (and in turn chanoramas) therefore they can only be used to calculate scaling factors in rare instances. We can however use the trepanned holes to verify the accuracy of any scaling factors which are automatically calculated from keyways and brick layer heights. Given in Figure 11 is a modified image of a single brick layer where we only include the region of the brick pertinent to this case study. By applying the techniques described in this paper to automatically locate and measure the widths of each keyway, and using the prior knowledge that a keyway is 51.5mm wide, we calculate a horizontal scaling factor of 0.2384 mm/px. Similarly using the automatically measured brick height and the fact that every brick layer for this particular station is 825 mm, we can calculate a vertical scaling factor of 0.2047 mm/px. The dimensions of the trepanned hole were automatically determined to be 102 pixels wide and 116 pixels high. By applying our automatically computed scaling factors, we can calculate the dimensions of the trepanned hole to be 23.49 mm wide and 23.745 mm high. As previously discussed trepanned holes have a known physical dimension due to being created a standard tool. This diameter is 23 mm which is in good agreement with the calculated dimensions using our automatically computed scaling factors.

Using a similar approach we can measure the dimensions of the crack present in the image shown in Figure 12. As before, we calculate a horizontal scaling factor of 0.2601 mm/px and a vertical scaling factor of 0.1770 mm/px. Using these scaling factors we calculate the width of the horizontal aspect of the crack highlighted to be 329 mm and the height of the vertical aspect of the crack to be 41 mm.
CONCLUSIONS

Accurate measurement of the dimensions of any defects observed during visual inspections is important when considering the continued operation of the fleet of AGR cores in the UK. We have presented a number of tools to automatically detect features of known physical dimensions and to measure their pixel dimensions required for calculating accurate scaling factors. We have also demonstrated that scaling factors calculated automatically using known features such as keyways and brick heights yield accurate results when used to calculate the dimensions of a trepanned hole. In turn, this provides confidence that the approach proposed in this paper can be used for accurately sizing cracks.

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References

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