AUTOMATED IMAGE STITCHING OF DOWN CHANNEL NUCLEAR REACTOR FUEL CHANNEL INSPECTION FOOTAGE

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ABSTRACT

Routine inspection of the nuclear reactor core is fundamental to the continued safe operation of any nuclear power plant. Inspection methods vary but a common approach is visual inspection. Visual inspections are performed routinely on the UK's seven Advanced Gas-cooled Reactors (AGR) and in this paper, we focus on that design. The inspection footage recorded is in the form of video. A typical inspection consists of six scans of each cylindrical channel, each with a 70 degree field of view to guarantee the entire inner surface of the fuel channel is inspected. These scans are recorded with the camera field of view focused on the side walls but it is also possible to record a view looking straight down the channel. This type of forward facing footage is known as down channel footage.

In this paper we demonstrate a novel framework for creating inspection images from down channel video footage. We demonstrate that it is possible to view both features of interest and defects in these images and compare them to inspection images stitched from regular footage. Down channel inspection images have a number of advantages compared with regular chanoramas including requiring only a single traversal of the fuel channel to record all the required footage and the illumination is much more uniform. While this paper focuses on unwrapping and stitching cylindrical nuclear inspection images from AGRs, the technique described could be adapted to stitch inspection data from other designs of reactor and industries where routine inspections are performed inside pipework.

Key Words: Image Stitching, Nuclear Reactor Inspection

1. INTRODUCTION

To ensure the safe continued operation of any nuclear power station and to justify any extensions on the plant's lifetime, routine inspection of reactor's core is essential. The purpose of these inspections to determine the physical health of the core and to identify any potential defects. The methods used to perform inspections vary for different station designs and common approaches include ultrasonic inspection which is used to inspect the Canada Deuterium Uranium (CANDU) [1, 2] design of reactors and visual inspection which is used for the Advanced Gas-cooled Reactor (AGR) design [3, 4]. Seven of the eight of the UK's fleet of nuclear power stations are of the Advanced Gas-cooled Reactor (AGR) design and in this paper, we focus on that design.

One of the main life limiting components of the AGR design is the graphite core. Visual inspections are performed routinely in a carefully selected subset of the fuel channels in the core. The inspection footage is recorded from a video feed from a specialized radiation hardened camera mounted on a specialized tool [5] designed to operate in the reactor core. This camera is mounted so that the field of view is looking down the fuel channels but it is possible to record the inside wall of the fuel channel using a mirror that is part of the inspection tool. The position of this mirror is controlled by a motor so it is possible to view either down the fuel channel or the side walls as required.

Typical inspection videos consist of 6 overlapping scans with a field of view of 70 degrees. Scans are recorded at 6 different orientations and for each scan the camera tool is rotated 60 degrees which allows the entire inner surface to be recorded. A typical inspection takes at least an hour and generates a large amount of video footage that has to be manually analyzed by inspection specialists which results in significant cost due to the station not producing power during an outage and this analysis is performed on the critical path. This analysis is aided by a specialist piece of software known as ASIST (Automated Software Image Stitching Tool) and was developed specifically for this purpose [6,7]. This software uses the 6 scans from the inspection footage to generate a single image known as a chanorama (fuel channel panorama) which spans the entire inner surface of the fuel channel. Fig. 1 shows two example chanoramas generated automatically using inspection footage. Using ASIST to generate composite images of defects and other features of interest in the fuel channels can save a significant amount of time in comparison to manually assembling video frames to perform analysis.

While a typical inspection records data of the inside wall of the fuel channel, it is also possible to record a view looking straight down the channel. This type of forward facing footage is known as down channel footage. In this paper, we demonstrate a novel framework for creating chanoramas using down channel footage. We demonstrate that it is possible to view both features of interest and defects in the down channel chanoramas despite them having a lower resolution compared with regular chanoramas. The down channel chanoramas are generated by identifying the appropriate elliptical section of down channel video frames and performing a transform to map (unwrap) them to a flat image. The appropriate width of elliptical pixel strip is unwrapped for every frame and the strips all stitched together. We compare the down channel chanoramas with regular chanoramas and highlight the advantages and disadvantages of each.

Down channel chanoramas (DCCs) have a number of advantages compared with regular chanoramas including requiring only a single traversal of the fuel channel to record all the required footage, the illumination is much more uniform, the computational resources required to produce them is significantly less and it takes much less time which could allow for them to be generated in real time. The benefits of only having to perform a single scan of any fuel channel instead of the usual six and faster computation times could result in a significant time saving for each channel which could result in shorter inspections and potentially a significant cost saving. While this paper focuses on unwrapping and stitching cylindrical nuclear inspection images from AGRs, the technique described could be adapted to stitch inspection data from other designs of reactor and industries where routine inspections are performed inside pipework.

1.1. Related Work

Visual inspection and visualization of the data has been applied to a number of tasks in the nuclear industry for the purposes of defect detection [4, 8, 9]and defect analysis [4, 10]. New methods using data available from current inspection tools use state-of-the-art techniques to visualize the inspection data in new ways. Law *et al.* [11, 12] develop a custom structure-from-motion framework to work with standard AGR inspection videos. This framework uses the video frames to build a 3D model of the inside of the fuel chan-

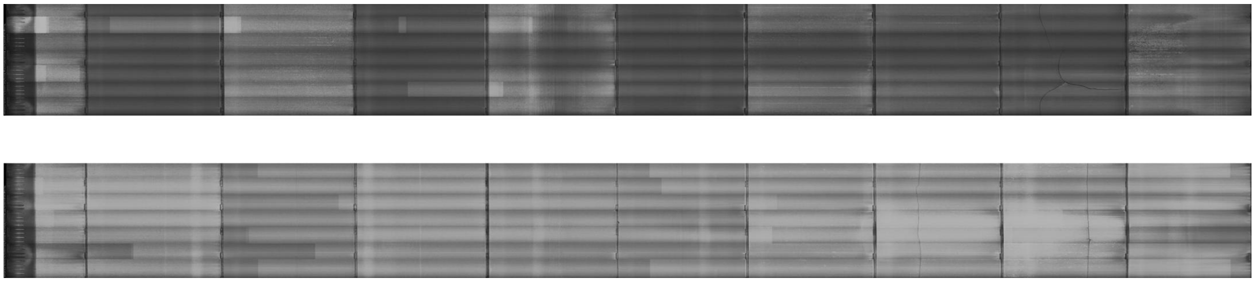


Figure 1. Example Chanoramas.

nels which allows regions of interest to be rotated and viewed from different angles. While this approach allows a lot of flexibility and freedom with using the inspection data, it is very computationally demanding to generate the 3D models. Research has also been performed to develop new pipework inspection tools for the nuclear industry. Summan *et al.* [13, 14] design and developed a new probe for the purpose of inspecting pipework. This new visual inspection system employed a fisheye camera and a structured light system to record the internals of pipelines. This work then focused on presenting the data gathered in a manner suitable for accurate analysis to be performed.

2. METHODOLOGY

In this section we present the methodology for using down channel footage to create down channel chanoramas. We consider two forms of down channel footage, stabilized and unstabilised. The unstabilised footage is the footage recorded when the camera is first inserted into the core before recording the six scans of the inside walls of the fuel channel and the inspection tool's stabilizing wheels are not deployed. This results in significant camera shake in this type of footage. Stabilized footage is recorded when the stabilizing wheels on the inspection tool are deployed while the camera transverses the fuel channel but this type of footage is not typically recorded during an inspection as it takes additional time for each channel which slows return to service. In addition to the stabilized footage having significantly less camera shake, the footage also has significantly better lighting and clarity due to the camera setup being optimized for recording standard side wall scans.

To create a down channel chanorama, a suitable region from every frame of the inspection video must be extracted. This region consists of elliptical ring of pixels as shown in Fig. 2.

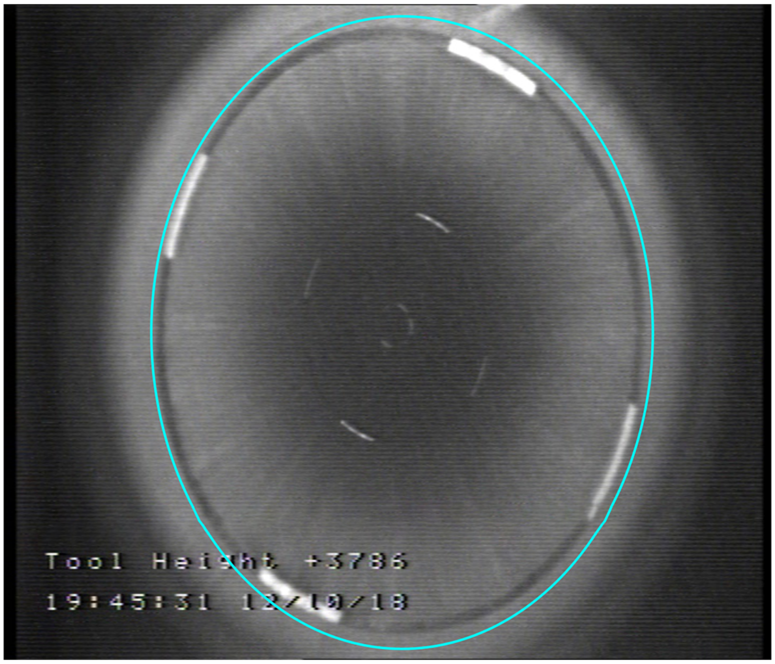
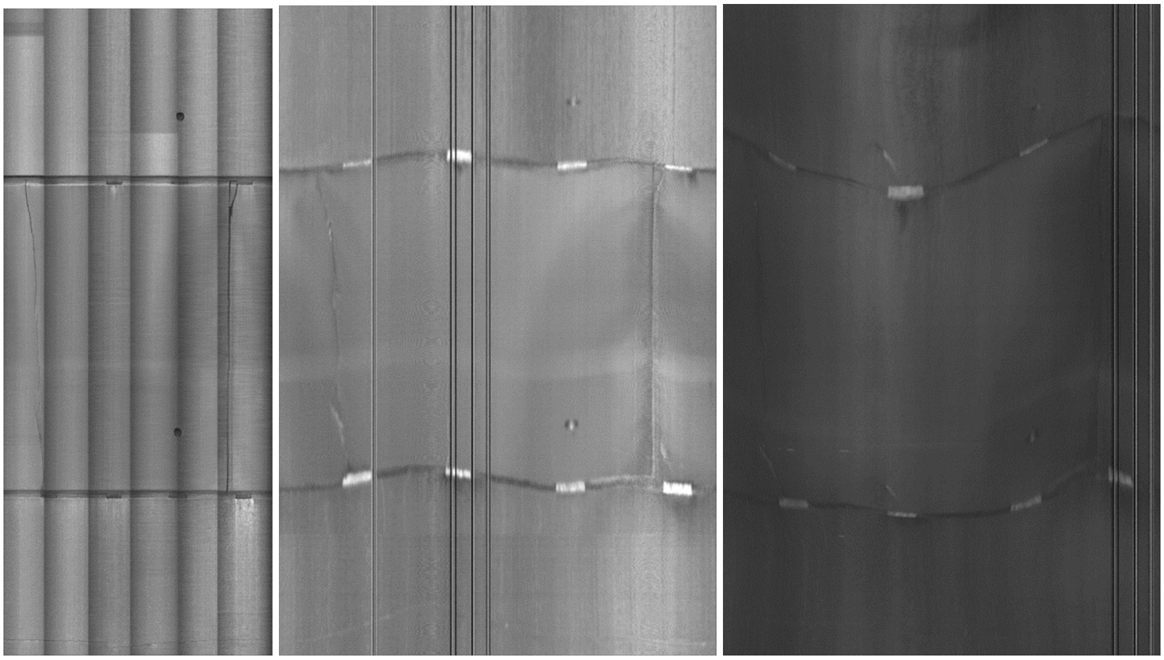


Figure 2. Ring of pixels to be extracted from this frame to generate DCC denoted by the cyan circle.

The optimal ring of pixels is selected manually by the user and this can be easily determined by using features within the frames such as brick interfaces as shown in Fig. 2. The width of the ring of pixels required is determined by the speed at which the camera transverses the core. The optimal width of pixels for standard inspections was found to be one pixel wide but we also demonstrate the effects of using wider rings of pixels in Section 3.1 For every frame, one ring of pixels is extracted and each ring of pixels is unwrapped and mapped to a fixed length row vector. This mapping is carried out by considering the Cartesian coordinates of each pixel in the ring and converting the coordinates to polar coordinates. It is then possible to sort the array of pixels by their angle relative to the positive x-axis and plot each ring as a single row of pixels. This row of pixels is then resampled to a fixed size using 1D interpolation. While it is not necessary to perform this mapping when using a 1 pixel thick ring, it is necessary when considering thicker rings and also in the case when we unwrap the entire frame as demonstrated in Section 2.1.

The DCC is constructed by stacking each row vector on top of each other. Further processing is performed to ensure the physical features (e.g. horizontal position of keyways and defects) in the image align with the standard chanorama. When considering the stabilized footage, it is sufficient to consider a fixed location ring of pixels as the camera shake is minimal. An example of a section of a chanorama generated using this method is shown in Fig. 3(b). Comparing this with Fig. 3(a), It is easy to resolve both the axial cracks and the trepanned holes*. It is also possible to apply the same approach to unstabilised footage from the same inspection. An example of the same region is given in Fig. 3(c). In this case the chanorama generated is significantly darker as the lighting was not optimized before recording this footage. We are also forced to consider a significantly smaller ring of pixels to ensure the region of interest does not leave the frame due to large variations in camera pose. The brick interfaces are very distorted due to this camera shake and limited diameter ring of pixels. The black vertical lines present in both types of DCC are due to the overlay text (see Fig. 2) present in every inspection video and can only be eliminated by recording footage with the overlay not present in the region of interest.



(a) (b) (c)

Figure 3. Comparison of chanorama types: (a) Original Chanorama (b) Stabilized Down Channel Chanorama (c) Unstabilized Down Channel Chanorama.

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[*] A trepanned hole is created when a cylindrical piece of graphite is extracted from the inside wall of the fuel channel for analysis. Trepanned holes serve as useful features in chanoramas to help determine if physical features can be resolved and to calculate the scales when sizing defects.

2.1. Unwrapping Down Channel Frames

It is also possible to unwrap the entire inner surface of the fuel channel observed in every down channel frame using the methodology described above. This is achieved by unwrapping a series of concentric rings of pixels which include the region of interest in their field of view. The region of interest to be unwrapped is shown in the upper region of Fig. 4.

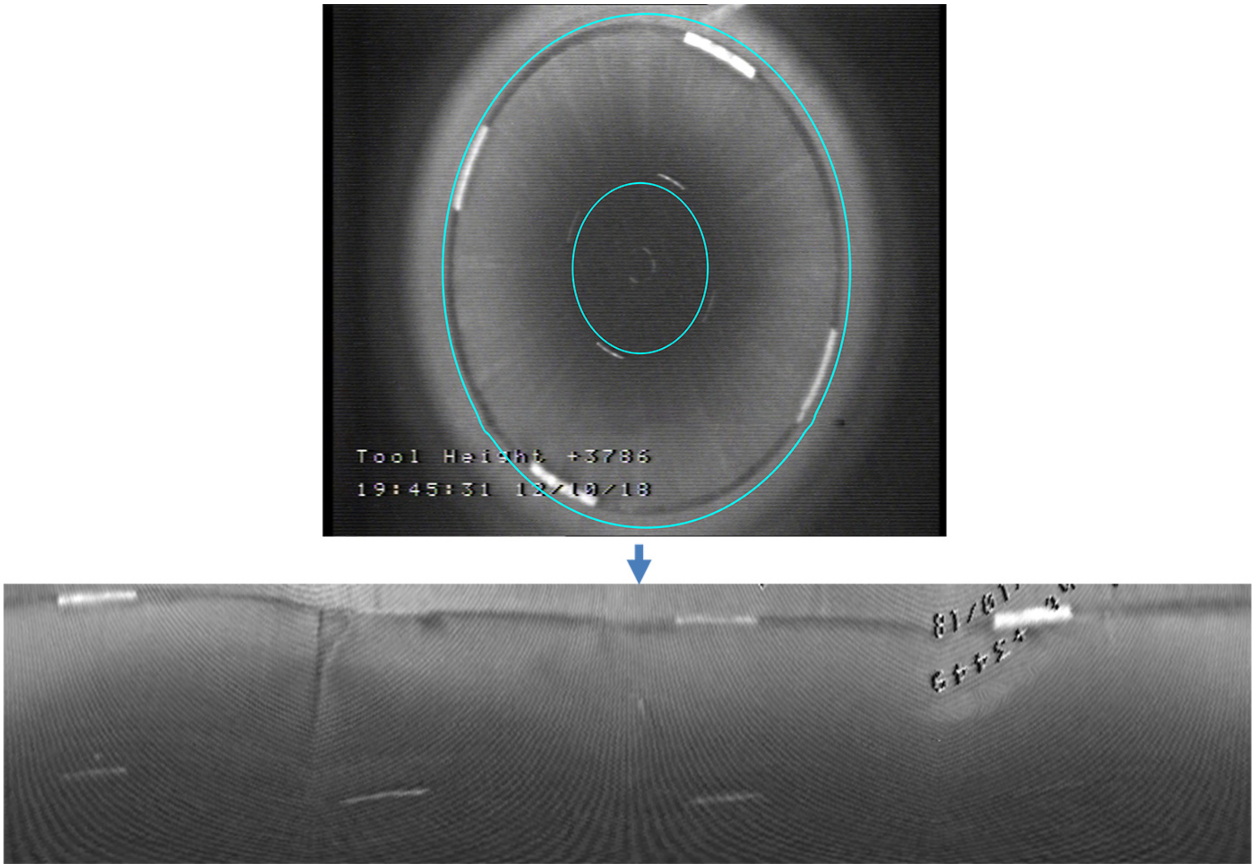


Figure 4. The region of interest to be unwrapped is the area between the two cyan circles. This cylindrical region is mapped to the rectangular frame in the lower part of the image.

Each ring of pixels will have a different diameter resulting in a different lengths when unwrapped therefore it is necessary to map each pixel in each ring to a fixed width row of pixels. By successively unwrapping each concentric ring of pixels and stacking each on top of each other it is possible to covert the cylindrical image of the fuel channel wall to a rectangular one. The example in Fig. 4 shows the frame to be unwrapped in the upper region and the resulting unwrapped image below. Fully unwrapping every frame is useful as it allows an inspection video with down channel footage frames and circular brick interfaces to be converted to a single rectangular video which spans the entire 360 degree field of view of the inside of the fuel channel which is not possible with regular scans.

3. RESULTS

In this section we present the results of applying the algorithm presented above to both stabilized and unstabilized down channel inspection footage. Given in Fig. 5 and Fig. 6 are two entire fuel channels which are particularly interesting as they both contain defects. For the method described in this paper to be useful, it is essential that all the features of interest that are observed in a standard chanorama can be resolved in a DCC. For comparison purposes, we present standard chanoramas, stabilized DCCs and unstabilised DCCs.

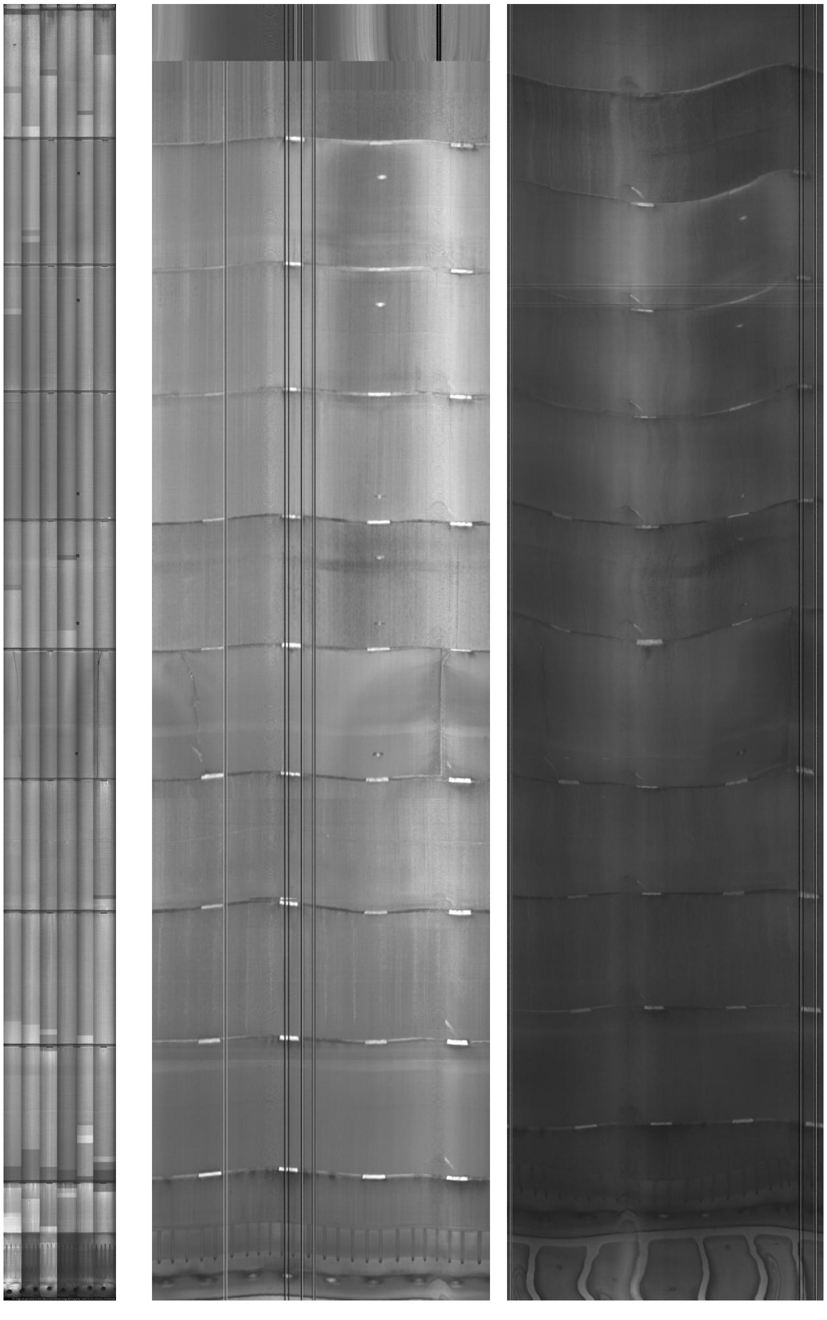
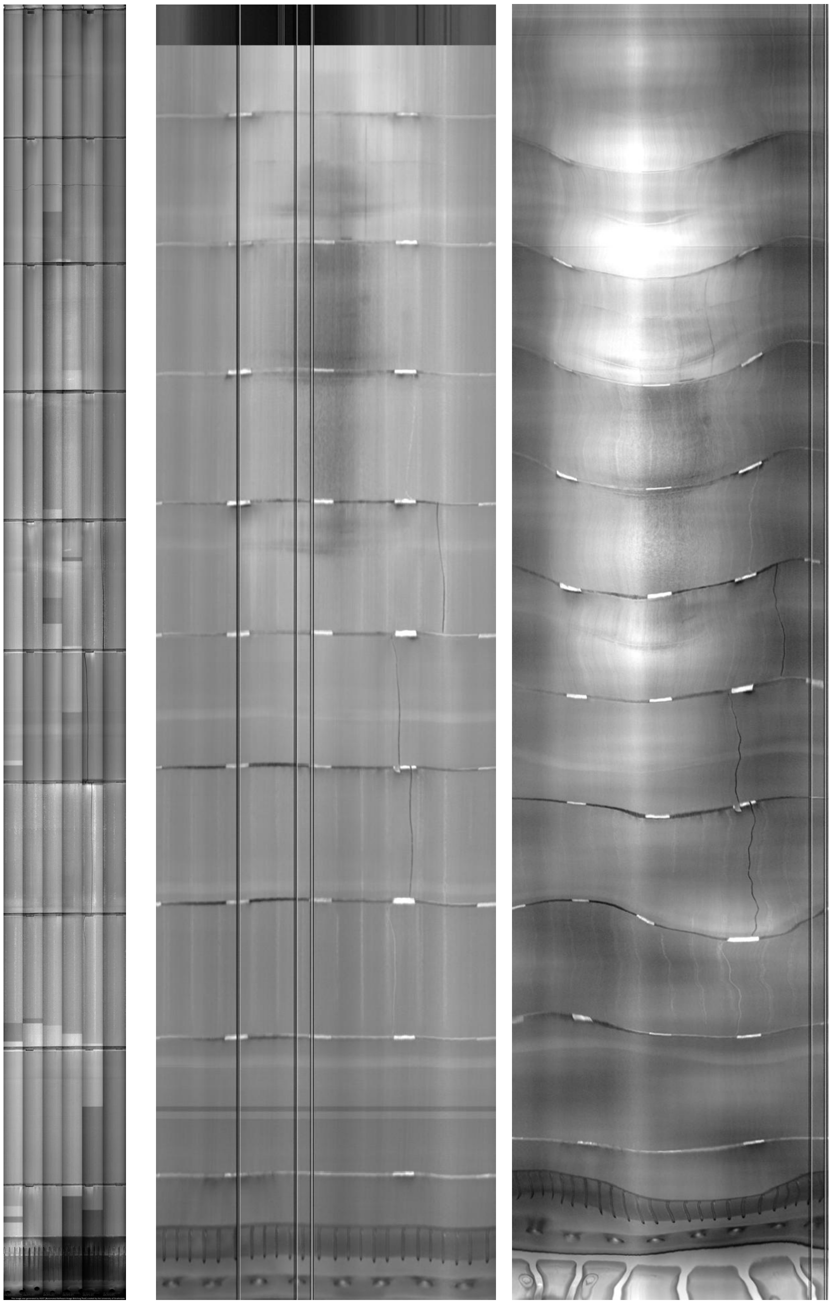

(a) (b) (c)

Figure 5. DCC comparison: (a) Original Chanorama (b) Stabilised Down Channel Chanorama (c) Unstabilised Down Channel Chanorama. Note the defects on the 4th and 5th brick layers in each chanorama.

Considering the fifth brick layer[†] in the first example chanorama Fig. 5(a), we can see two axial cracks.

[†] brick layers are counted from the bottom up



(a) (b) (c)

Figure 6. DCC comparison (a) Original Chanorama (b) Stabilized Down Channel Chanorama (c) Unstabilised Down Channel Chanorama

These are easily observable in Fig. 5(b) but much more difficult to observe in Fig. 5(c) due to lighting and blur. Other features such as keyways [‡] and trepanned holes are also clearly visible. The keyways present as the white rectangular blocks on the brick interfaces and the trepanned holes present as ellipses in the body of the brick layer. The trepanned holes appear as ellipses as this approach introduces distortions into the unwrapped images due to viewing the features of interest at a steep angle.

[‡] keyways are used to interlock the brick layers

Another set of example chanoramas is given in in Fig. 6. Considering the third and seventh brick layers in Fig. 6(a) and (b), it can be seen that very narrow axial cracks appear more salient on the DCC when compared with the regular chanorama. This may be due to the way the lighting interacts with the graphite for very narrow cracks but demonstrates a distinct advantage of the DCC. The other cracks in brick layers 4,5 and 6 are also very clearly visible in both the stabilized and unstabilised DCC. Keyways and brick interfaces are also clear for both types of DCC. The extra clarity in this particular unstabilized DCC is likely due to an adjustment in lighting before the unstabilised down channel footage was recorded.

It is clear from the examples presented that the image quality of the stabilized DCC is considerably better than that of the unstabilised DCC and it is much easier to observe defects and features of interest. This is due to optimal lighting being used for the stabilized DCC, a larger ring of pixels being extracted from every frame and minimal camera shake. The are a number of advantages to using DCCs compared with standard chanoramas. Comparing DCC with regular chanoramas we can see that the illumination is more uniform than for the individual scan strips of a regular chanorama. This is due to the fact the lighting is provided by a ring of standard LEDs as opposed to two high intensity LEDs. We also demonstrate that certain axial cracks are more salient in DCC compared with standard chanorama. DCCs also only require ones scan to gather all the data needed for their generation so if it is possible to use DCCs instead of regular chanoramas, this would offer a significant time saving in the inspection process. This speed advantage is further compounded by the fact that generating a DCC is much faster than a standard chanorama and requires significantly less computational resources. The main disadvantages of DCC compared with regular chanoramas is curvature of the brick interface and the distortion of features such as the keyways and trepanned holes due to the steep observation angle. However these disadvantages would not prevent DCCs being a useful tool to quickly inspect a fuel channel and determine if there are any large defects present.

3.1. Chanoramas Generated Using Multiple Rings

Considering the 4th brick layer of Fig. 5(b) demonstrates that it is quite difficult to observe a circumferential crack in a stabilized DCC. This is due to the effect of viewing the crack at a steep angle and the fact that horizontal features are represented by fewer pixels compared with vertical features. In an effort to improve the saliency of these cracks, we investigated generating a DCC using multiple concentric rings of pixels. In practice the best way to achieve this for every single frame is to unwrap the entire region of interest for every frame, as shown in Fig. 4. Using the appropriate number of top rows of pixels[§] from the rectangular image for each frame, it is possible to generate a DCC using different numbers of concentric pixel rings. Fig. 7(a), 7(b) and 7(c) show the same section of a DCC generated using one, two and three rings of pixels respectively. Fig. 7(b) does not show an increase in quality and Fig. 7(c) demonstrates a decrease in quality due to repeating features. This analysis demonstrates that this approach actually degrades the unwrapped image quality for the current inspection footage but could still be useful for footage where the camera was moving significantly faster.

3.2. Effect of Location of Pixel Ring of Interest

The best quality DCCs are generated when the ring of pixels used has the largest possible radius. This can be demonstrated by generating a series of DCC of the same section of fuel channel with different rings of pixels and comparing the final images. Considering Fig. 8 and 9 which were generated using the same frames but using the ring of pixels denoted by the green circle on the left of each image we see that increasing the radius of the ring of pixels improves image brightness, detail and clarity significantly. The disadvantage of the larger ring of pixels is that the overlay on the original video footage introduces a series

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[§] these represent concentric rings of pixels from the original frame

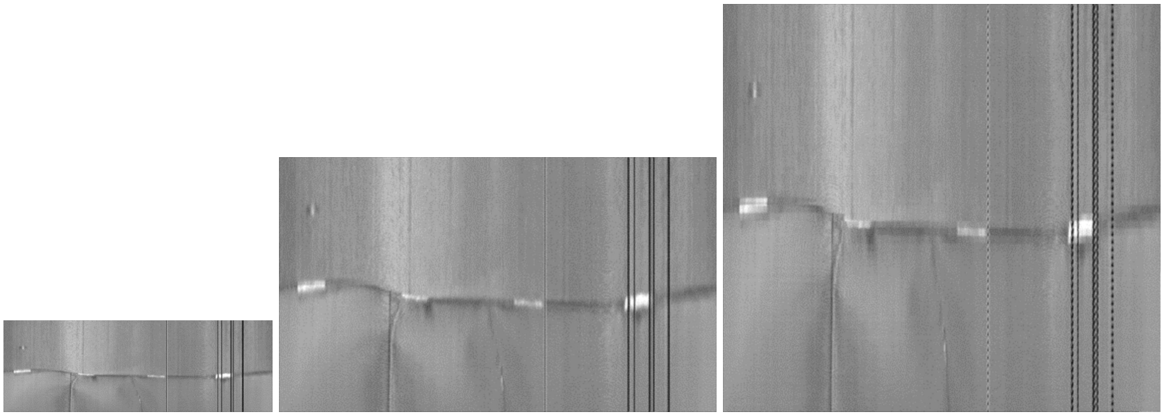
(a) (b) (c)

Figure 7. Comparing a section of chanorama generated using one ring of pixels (a), two rings of pixels (b), and three rings of pixels (c).

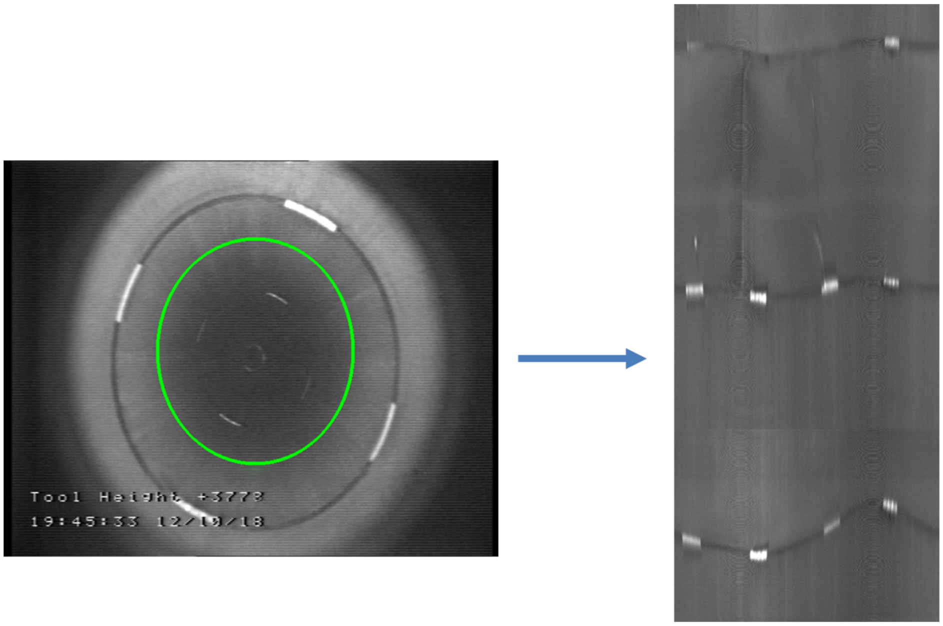

Figure 8. Ring of pixels (denoted by green circle) used to construct section of chanorama on the right.

of persistent black or white vertical lines into the chanorama. This issue may be overcome in the future by recording video footage with no overlay.

4. CONCLUSIONS

In this paper we present a methodology for producing chanoramas from forward facing or down channel inspection footage recorded during routine AGR inspections. Two types of down channel footage were considered; unstabilized footage and stabilized footage recorded specifically for this purpose. This methodology performed very well and the initial results are very promising. The main features of interest such as cracks, brick interfaces, trepanned holes and keyways are clearly observable. Constructing this type of chanorama has the potential to speed up the inspection of a channel by reducing the number of scans. We also present an algorithm which allows the entire region of interest in a cylindrical frame to be unwrapped

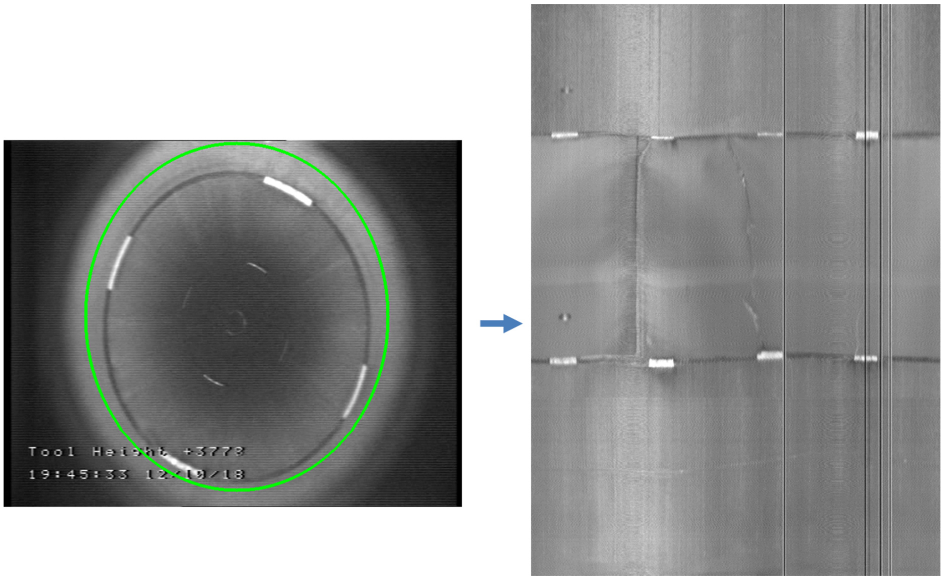

Figure 9. Ring of pixels (denoted by green circle) used to construct section of chanorama on the right.

into a rectangular frame. This approach allow the generation of unwrapped video footage which spans the entire inner surface of the fuel channel from a single scan. Finally, we present the results of further analysis considered to improve the quality of the generated DCC. This included an investigation into the optimal location for the ring of pixels used from each frame and the use of multiple concentric rings of pixels. It was concluded that the optimal ring of pixels should have the largest diameter possible to generate the brightest DCC. The large ring of pixels also minimizes distortion in the observed brick interfaces. The disadvantage of this approach is the introduction of vertical lines in the final DCC due to the video frames overlay. Using concentric rings of pixels did not improve image quality due to repeating physical features in the frames. This approach would be useful if the camera was moving very quickly to ensure the entire inner surface of the fuel channel is represented in the final DCC.

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