Nuclear Engineering and Design 300 (2016) 57–66

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Automated in-core image generation from video to aid visual inspection of nuclear power plant cores

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HIGHLIGHTS

- A method is presented which improves visual inspection of reactor cores.
- Significant time savings are made to activities on the critical outage path.
- New information is extracted from existing data sources without additional overhead.
- Examples from industrial case studies across the UK fleet of AGR stations.

ARTICLE INFO

Article history:
Received 6 May 2015
Received in revised form
23 November 2015
Accepted 29 November 2015

M. Instrumentation and control

ABSTRACT

Inspection and monitoring of key components of nuclear power plant reactors is an essential activity for understanding the current health of the power plant and ensuring that they continue to remain safe to operate. As the power plants age, and the components degrade from their initial start-of-life conditions, the requirement for more and more detailed inspection and monitoring information increases. Deployment of new monitoring and inspection equipment on existing operational plant is complex and expensive, as the effect of introducing new sensing and imaging equipment to the existing operational functions needs to be fully understood. Where existing sources of data can be leveraged, the need for new equipment development and installation can be offset by the development of advanced data processing techniques.

This paper introduces a novel technique for creating full 360° panoramic images of the inside surface of fuel channels from in-core inspection footage. Through the development of this technique, a number of technical challenges associated with the constraints of using existing equipment have been addressed. These include: the inability to calibrate the camera specifically for image stitching; dealing with additional data not relevant to the panorama construction; dealing with noisy images; and generalising the approach to work with two different capture devices deployed at seven different Advanced Gas Cooled Reactor nuclear power plants. The resulting data processing system is currently under formal assessment with a view to replacing the existing manual assembly of in-core defect montages. Deployment of the system will result in significant time savings on the critical outage path for the plant operator and will allow improved visualization of the surface of the inside of fuel channels, far beyond that which can be gained from manually analysing the raw video footage as is done at present.

1. Introduction

Many of the world's nuclear power plants are approaching, or have exceeded their initial design lifetimes. These initial lifetimes were based on conservative estimates of degradation, and there is the opportunity to extend the operational lifetimes of these plants. In the US for example, there is the light water reactor sustainability (LWRS) program which is looking to support the operation of the fleet of light water reactors to 60 years and beyond. In the UK, several of the 2nd generation advanced gas-cooled reactor (AGR) power plants have been granted lifetime extensions, with a target of an average of 7 years across the fleet (Houlton, 2013). As the plant components age, there is an increasing need to understand their health and to predict

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Abbreviations: AGR, Advanced gas-cooled reactor; SIFT, Scale-invariant feature transform; RANSAC, RANdom SAmple consensus.

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http://dx.doi.org/10.1016/j.nucengdes.2015.11.037

how they will look in the future to ensure continued safe operation.

Two main methods of providing information to support the case for lifetime extension are (1) through condition monitoring, where data relating to the health of the plant is gathered during routine operation, and (2) through inspection, where the plant is shut down and a portion of it is inspected. As well as the safety requirements, there are financial implications associated with outages, as each day a UK AGR is operational, equates to approximately £0.5 M in income.

In the case of the AGR plants, the graphite core is a life-limiting component (along with the boiler systems), and inspection of fuel channels provides insight into the condition of the core. Each reactor consists of around 300 fuel channels and, at the start of life, only a few fuel channels (typically four) were inspected. In 2015 this number has risen to 31 for the oldest plants and the channels to be inspected are selected based on various competing criteria (Watson, 2013). This results in an increase in the volume of data that needs to be assessed before the plant is returned to service, and this assessment lies on the critical outage path. As a result, the application of automated or semi-automated techniques to aid the processing and analysis of this data in a robust, repeatable, and auditable manner has significant value. In future, this will also facilitate an increased number of channel inspections which could positively impact any decisions based on economic factors associated with plant inspection.

One approach for improved data handling would be to design and build new inspection tools which optimize data capture and automatically process the data acquired to provide sophisticated decision support. However, the development and deployment of new inspection equipment, particularly that which is to be inserted into the harsh environment of a reactor core, is very expensive. Leveraging data captured using existing equipment is therefore desirable as it minimizes additional financial outlay. However, the feasibility and complexity of this approach is determined by the constraints of the existing data capture process which may not align directly with the proposed use of the data.

This paper describes the application of advanced signal and image processing techniques to existing in-core inspection TV footage, with the aim of producing *chanoramas* – full 360° panoramas of the inside of the fuel channels. The contributions made in this paper include:

1. integrating the use of *a-priori* knowledge about the camera pose and position to overcome issues of the largely featureless surface areas of the graphite core which restricts the application of more traditional image stitching techniques (Szeliski, 1994; Bay et al., 2008; Bay, 2006; Brown, 2003; Tuytelaars and Mikolajczyk, 2008; Szeliski, 2004),
2. generating these novel *chanoramas* using data from across the nuclear fleet in the UK in a reliable, repeatable and timely manner, with minimal human intervention,
3. dealing with variation in: camera orientation, illumination, noise and other distortions which arise from a data capture system with the absence of the ability to calibrate the camera,
4. deployment of software which takes a channel inspection video as an input and automatically generates a chanorama of the inspected channel as an output, without the need for manual intervention.

More generally, a key contribution of this paper is that we present a technique which makes significantly better use of an existing data set. The proposed approach allows existing inspection videos to be rendered and viewed as a single image where the entire fuel channel inspection video can be seen in the context of the channel itself. The techniques proposed herein can be applied to any video which is captured in a similar format to that used to capture the videos used in this study.

The remainder of this paper is laid out as follows: Section 2 describes: the formation of the AGR cores; the existing inspection techniques; and manual methods for data analysis as well as highlighting the challenges for automating the image processing. Section 3 provides a brief summary of related work and, in Section 4, our new system for converting inspection videos into chanoramas is described in detail. In Section 5 we discuss the results of applying our techniques to process a number of videos and we compare our images to those produced for the same channel using the existing manual techniques before concluding in Section 6.

2. Inspection of advanced gas-cooled reactor cores

Seven of the nine nuclear power plants in operation in the UK are of the AGR design. The AGR graphite core is constructed from layers of cylindrical graphite bricks, and each layer consists of around 300 fuel bricks plus interstitials which are physically keyed together. Cores generally consist of 11 brick layers, although this varies from plant to plant, and each of the bricks stands around 800 mm tall. The graphite core is configured in this way to form various channels to accommodate fuel, control rods and control the passage of the CO_2 gas coolant. As well as providing the physical structure for housing the fuel, the core also acts as a neutron moderator. Under fast neutron irradiation and through the process of radiolytic oxidation, the properties of the graphite bricks, such as their dimensions, strength and Young's modulus all change, and under certain conditions the bricks can crack. Tracking these changes and their effects through regular monitoring and inspection of the core (Murray, 2013; Bloodworth, 2012; Wallace et al., 2012) can provide supporting evidence that indicates the cores are in good condition and remain fit for purpose.

2.1. Fuel channel inspection and video capture

During an outage, part of the inspection process uses tools named CBIU (Channel Bore Inspection Unit) and NICIE (New In-Core Inspection Equipment) which are lowered into each of the AGR fuel channels selected for inspection (Cole-Baker, 2007). These tools are equipped with various sensors including, a video camera, which are used to acquire data from inside the channel. Using the tool to record videos of successive vertical scans of the channel wall at different camera facings with sufficient overlap between the scans ensures that full coverage of the internal channel surface is obtained. During these scans, detailed measurements of the channel bore are also recorded. If anything unusual is observed during these scans, such as a defect in the channel wall, the region of the channel that contains the defect is revisited, and additional video data known as "crack following footage" is recorded. This additional footage is gathered solely for the purpose of manually generating montages which are used to assess and quantify the defect, and no further bore measurements are taken.

2.2. Existing data analysis techniques

At present, all data analysis is performed manually by an expert operator. As a result, the existing manual montage generation process is time-consuming and labor-intensive, requiring suitable frames to be identified and extracted from the footage and manually assembled into the montage using third party image manipulation software. The resulting montages are assessed along with other measurements taken during the inspection to make a qualified statement to support return to service of the plant. The method proposed in this paper for automatically generating chanoramas from just the vertical scans: speeds up the generation of crack montages; provides additional images of the surrounding area; and