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Towards Extracting 3-D Structural Representations of AGR Core Fuel Channels from 2-D In-Core Inspection Videos

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Abstract: Remote Visual Inspection (RVI) of Advanced Gas-cooled Reactor (AGR) nuclear power stations allows engineers to gain an understanding of the AGR graphite core health by investigating the incorporated fuel channels. During planned, periodic outages, video footage of the pre-selected fuel channels is acquired using specialist inspection tools and is subsequently taken offline for further analysis using visualization techniques. Current methods of visualization however provide limited structural information due to the loss of depth information as a direct result of the image acquisition process. This paper introduces a new bespoke 3-D reconstruction framework to recover lost depth information to produce 3-D point cloud reconstructions of fuel channels from inspection videos. We also present here a new, lab based, experimental rig setup with which we effectively captured data under lab controlled conditions to verify our 3-D reconstruction algorithms. Our proposed method is tested on 2-D in-core inspection videos in addition to the footage captured within laboratory conditions and outperforms state-of-the-art incremental reconstruction frameworks whilst producing a more representative 3-D point cloud for improved in-core visualization.

Keyword: Advanced Gas-cooled Reactor, Visual Inspection, Structure-from-Motion

1 Introduction

Within the U.K, there are 7 Advanced Gas-cooled Reactors (AGR) currently in operation which are close to or have already exceeded their original estimated design lifetime. As the reactors age, there is an increased demand to accurately monitor and visually inspect reactor components which directly contribute to the operational lifespan limitations of the AGR such as the graphite core [1]. The AGR graphite core is comprised of a lattice structure of hollow, cylindrical interconnected graphite bricks forming both fuel channels which accommodate fuel, and control rod channels which provide the primary control and shutdown method. The graphite also acts as the moderator for the nuclear reaction. During reactor operation, radiolytic oxidation and fast neutron irradiation results in physical and structural degradation of the graphite bricks resulting in structural defects in the fuel channel such as cracks [2].

Remote Visual Inspection (RVI) is one technique deployed by inspection engineers to observe operational reactor degradation and this is done using inspection tools such as the Channel Bore Inspection Unit (CBIU) and the New In-Core Inspection Equipment (NICIE2) tool [1] during scheduled outages. Around 10% of the channels are pre-selected for analysis based on various competing criteria [3] and are vacated of fuel prior to inspection. The inspection tools are then lowered into the selected fuel channels, and forward facing video footage is acquired as the tool descends into the channel. Once it reaches the debris pot at the bottom of the fuel channel, a mirror is engaged which changes the observable orientation onto the channel wall. Afterwards, successive scans of the channel wall interior are obtained at a step size of $\pm 60°$ with approximately $10°$ of visible overlap to ensure full circumferential coverage of the inside of the channel. During this phase, the engineers performing the inspection will take notes on regions of interest that warrant further investigation and require to be revisited for further data capture known as crack following.

Once, the footage is obtained, it is taken offline where it is manually analyzed and montages of regions of interest are assembled directly from the crack following footage. The current techniques however are very time consuming and the reactor cannot be returned to power until the montage assembly and examination of the footage is complete. Nonetheless, the current technique deployed provides minimal structural information about the channel which could be very valuable when profiling and categorizing structural defects due to the loss of depth as a direct result of the

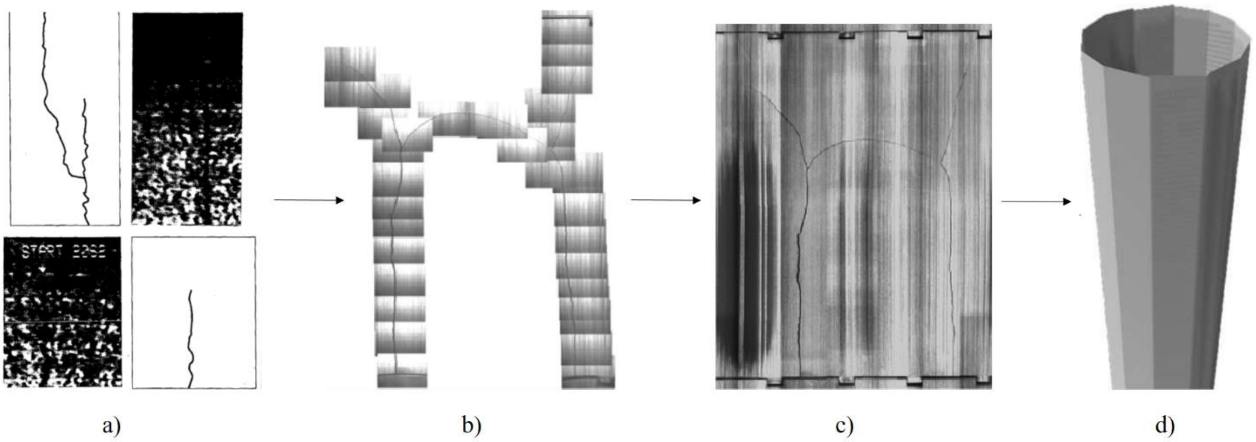


Fig.1. a) Footage from video tape alongside corresponding hand-drawn interpretations [5]. ; b) Manually stitched image of a region of interest. ; c) A panoramic image of the same defect (cropped to the individual brick layer); d) Proposed 3-D Structural representation of the same AGR channel generated using bore feeler measurement data acquired using the inspection tools.

image acquisition process. Therefore, the underlying motivation for this paper is to provide a framework that can be used to extract depth information directly from RVI inspection videos using an image processing technique called Structure-from-Motion (SfM). It is anticipated that extracting depth information using the proposed approach will allow an improved understanding of the reactor core health whilst utilizing pre-existing historical and future inspection footage [4]. Within this paper, progress towards obtaining 3-D structural representations of AGR fuel channels using our own bespoke reconstruction framework are presented. Our reconstruction framework is applied to footage obtained within controlled, laboratory conditions using an experimental rig setup containing three interlocked Giloscarbon graphite bricks in addition to real AGR RVI footage obtained from within the reactor cores during inspection. Reconstruction results generated using both sets of footage are subsequently benchmarked against state-of-the-art reconstruction frameworks.

2 Visual Inspection of AGR fuel channels – An Overview

2.1 Manual Interpretation

Manual interpretation and image stitching was one of the first methods of visual inspection deployed within the AGR reactors by inspection engineers. Approximately 25 years ago, visual inspection engineers would use images stills printed from analog video tape and hand-drawn representations of any defect within the channel to analyze and characterize it [5]. These images (as seen in Fig.1a)) however could take up to a week to generate due to the digitization process and were limited to defects picked up on individual orientation scan of the AGR fuel channel.

As the reactor has aged, inspection tools such as CBIU, NICIE and NICIE2 have been commissioned to capture visual and other sensory data such as bore diameter measurements. The inspection cameras on these tools provide increased video resolution allowing for a more comprehensive visual inspection which is still used to this day. With the improved visual fidelity, engineers manually stitch images to form individual montages of defects (as seen in Fig.1b)) which can subsequently be studied and analyzed to quantify the defect before the station is returned to power, provided it is safe to do so. This method enhanced the visualization of defects whilst reducing the turn-around time from a week to approximately one working day to generate the images required for further analysis. This is the current method of visualization used during AGR fuel channel inspection.

2.2 Chanoramas

Chanorama (Channel Panorama) is the name given to a 360° panorama generated using video footage captured from within the AGR fuel channels. Chanoramas can be created using the ASIST (Automated Software Image Stitching Tool) software tool created by researchers at the University of Strathclyde to provide inspection engineers with an efficient, repeatable, automatic method for generating defect montages

a) b) c)

Fig.2. a) Downward facing camera deployed when camera descends to the bottom of the channel; b) Brick interface within the AGR RVI footage; c) Atypical image taken between brick interfaces.

while using all of the available video data to allow full channel visualization in a snapshot [1][3]. With ASIST, inspection engineers can autonomously generate a full 2-D chanorama of the AGR fuel channel interior in approximately 20 minutes.

The ASIST process begins by identifying the first and last frames of each orientation scan. Then, a horizontal window of 5 pixels (corresponding to those which have changed due to the motion of the inspection tool) is extracted from each frame and vertical image strips are formed through accretion of the windowed pixels [6]. Afterwards, each vertical strip is aligned using binary edge detection and cross correlation [1][6][7] and subsequently merged to form a chanorama. An image of a single brick layer cropped from a full chanorama can be observed in Fig.1c). ASIST has now been successfully evaluated in parallel with the existing manual image stitching process and it is anticipated that soon the case will be made to switch from the existing manual process to an automatic one using the software.

2.3 3-D Reconstructions

3-D interpretation of AGR RVI footage was first introduced in West et al [1] through the use of anaglyphic imagery and ‘pivot’ videos which both produce an illusionary 3-D stereoscopic effect. These techniques can be useful, especially by allowing a user to effectively simulate the act of pivoting around a region of interest within the channel to provide a view from multiple angles and allow inspection engineers to make a more informed decision. However, this technique doesn’t provide any depth information which could prove useful for visualization of the brick structure or examining the characteristics of defects within the channel. SfM is an image processing technique which can be used to recreate 3-D reconstructions of a scene or object observed within a 2-D image sequence. To extract 3-D information from the fuel channel directly from AGR RVI footage, previous works by the authors [4][7] introduced the application of generic SfM [8][9] to AGR RVI footage. The underlying principle of SfM is to identify correspondences within an image sequence or dataset of images before estimating the 3D location of each valid 2D correspondence using triangulation between the conforming views. This forms a point cloud, a sparse 3-D representation of the scene observed within the images. Concurrently, the camera pose and trajectory pertaining to each image in the sequence are also calculated in relation to the 3-D points observed.

As explained in [4] and evidenced in Fig.2, the images in the AGR RVI footage often lack or have a very small number of distinct and stable features which techniques such as SfM rely on heavily to provide meaningful reconstructions. For this reason, state-of-the-art SfM techniques often struggle to produce representative reconstructions of AGR fuel channels that exceed a single brick layer as demonstrated in [4]. Furthermore, the inconsistent viewing conditions caused by inspection engineers varying camera focus and illumination in addition to the lack of traditional camera calibration data habitually required when applying SfM introduces additional challenges for reliably tracking and triangulating the correspondences. Therefore, in this paper, we explore the application and development of a new bespoke SfM framework and benchmark its performance using both AGR RVI footage and footage acquired from our lab based inspection rig.

3 Methodology

A generic 3-D reconstruction framework can be segregated into two key modules: Correspondence

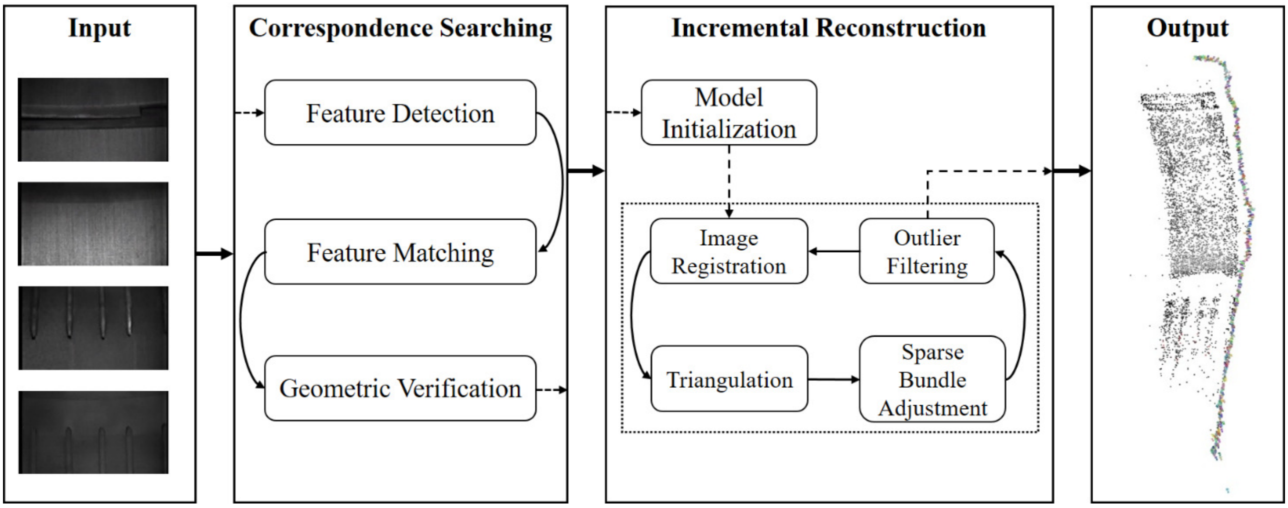


Fig.3. Visualisation of the implemented SfM framework for the reconstruction of AGR graphite bricks (using both laboratory and real RVI footage).

Searching and Reconstruction as shown in Fig.3. This section provides a brief overview to the techniques utilized within our proposed bespoke reconstruction framework developed using MATLAB with the aim of reconstructing 3-D point cloud representations of AGR fuel channels directly from visual inspection footage.

3.1 Correspondence Searching

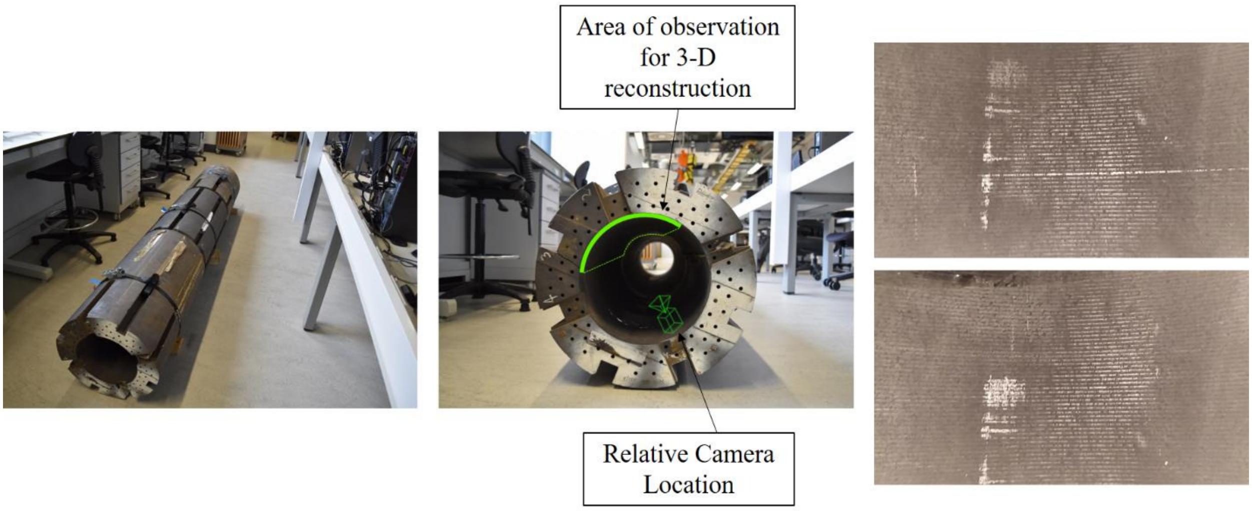
Correspondence searching is a method which incorporates three different sub-routines: Feature detection, feature matching then geometric verification. Feature detection is first applied to detect features within an image such as edges, blobs or other distinctive components and for each detected feature, a descriptor is created which describes the characteristics of the local neighborhood of pixels surrounding the feature. Feature matching then analyzes the descriptors and matches them to similar feature descriptors extracted from other images using similarity or distance measures. The final stage is to then verify that identified correspondences match under the assumption that the consensus of detected feature matches will all undergo a similar geometric transformation [4].

Within reference to Fig.3, to perform feature detection, the Scale Invariant Feature Transform (SIFT) [10] is chosen to extract features and create representative descriptors due to their invariance to illumination and scale changes. The descriptors from each image are then matched using the squared Euclidean distance metric to determine visual correspondences. Due to the lack of features observed in RVI footage (as seen in Fig.2c)), the returned feature matches are often ambiguous due to the repetitive nature of the brick texture. To compensate, a knowledge-based approach is implemented to constrain the possible match location into a small, bounded window [4]. This is made possible through our knowledge that the camera moves at a fixed speed and, therefore, between each captured frame, matching features should lie within a predetermined region which can be estimated. Afterwards, a well-known outlier rejection method named RANSAC (RANdom Sampling and Consensus) is applied to geometrically verify matches and remove erroneous matches that remain within the bounded window region.

3.2 Incremental Reconstruction

During inspection, each camera view has a limited view of the entire AGR fuel channel structure at any one time. Therefore, when reconstructing a 3-D representation of the channel, it must be constructed in a cumulative fashion so that a model can be generated as the camera moves up and down within the AGR fuel channel. Techniques such as Global or Hierarchical SfM are unsuitable since they consider all views at the same time or subsets of views, meaning during repetitive or cyclic environments as observed within the inspection footage, the resulting reconstructions can be erroneous [4]. Therefore, an incremental reconstruction framework is proposed as the most suitable approach for this application.

The reconstruction process within our framework is initialized on the first image pair captured by the



a) b) c)

Fig.4. a) Image of the three AGR graphite bricks secured together; b) Image of the inside of the interlocked graphite bricks with labelled area of observation and relative camera location**;** c) Images acquired within the graphite bricks. Note the vastly improved image quality in comparison to Fig.2c).

camera and correct initialization is essential to the reconstruction quality [9]. To ensure a very strong match is obtained between the first two images $I_1 \rightarrow I_2$, a minimum of 350 feature matches (determined empirically) between the initial seed pair is required by our framework. If not, we iteratively apply the SIFT feature extraction algorithm while lowering the matching threshold and applying local constraints until enough stable matches are found. As each image is registered and subsequently triangulated, the correspondences detected are tracked across a minimum of 3 views and a maximum of 10 views to improve the accuracy of the triangulation of the corresponding 3-D points. After the triangulation of the points relevant to the newly registered image, a refinement procedure known as Bundle Adjustment (BA) is applied where the 3-D point is subsequently projected back onto the image. A minimization process to reduce the reprojection error is subsequently performed between the 2-D feature location and the projected 3-D point location. Through minimization of the reprojection error and filtering outliers that exceed a certain error threshold, the 3-D point locations can be further refined making the sparse representation more robust. Within our application, Sparse Bundle Adjustment (SBA) is applied to take advantage of the sparsity of the parameters that are to be minimized which, in turn, reduces computation time [9][11].

4 Results

4.1 Experimental Setup

We have captured data from an experimental lab based rig comprised of three Giloscarbon graphite bricks (shown in Fig.4a)) which are interlocked to imitate a small sub-section of an AGR fuel channel. To allow the rig to form an accurate microcosm of conditions observed within an AGR reactor, two bricks contain intentionally induced cracks to simulate structural defects that can be observed within AGR RVI footage. With this setup, the aim is to capture images in a way that closely emulates the visual inspection process observed within the RVI footage when investigating the channel wall. For the purposes of this paper, reconstructions using a single orientation scan of an individual brick is used where the camera was translated along the inside of the brick at a set distance from the channel wall. The relative camera location and the area of observation is highlighted in Fig.4b). Visual inspection footage was acquired from the lab based inspection rig using a downward facing camera with a spatial resolution of 1920×1080 at 30fps. The camera was manually maneuvered inside the brick whilst simulating the inspection protocol observed within the RVI footage. Image stills from this process can be seen in Fig.4c). The laboratory footage resolution is down sampled to 720×405 to approximate the resolution of AGR RVI footage (720×400 when the inspection tool

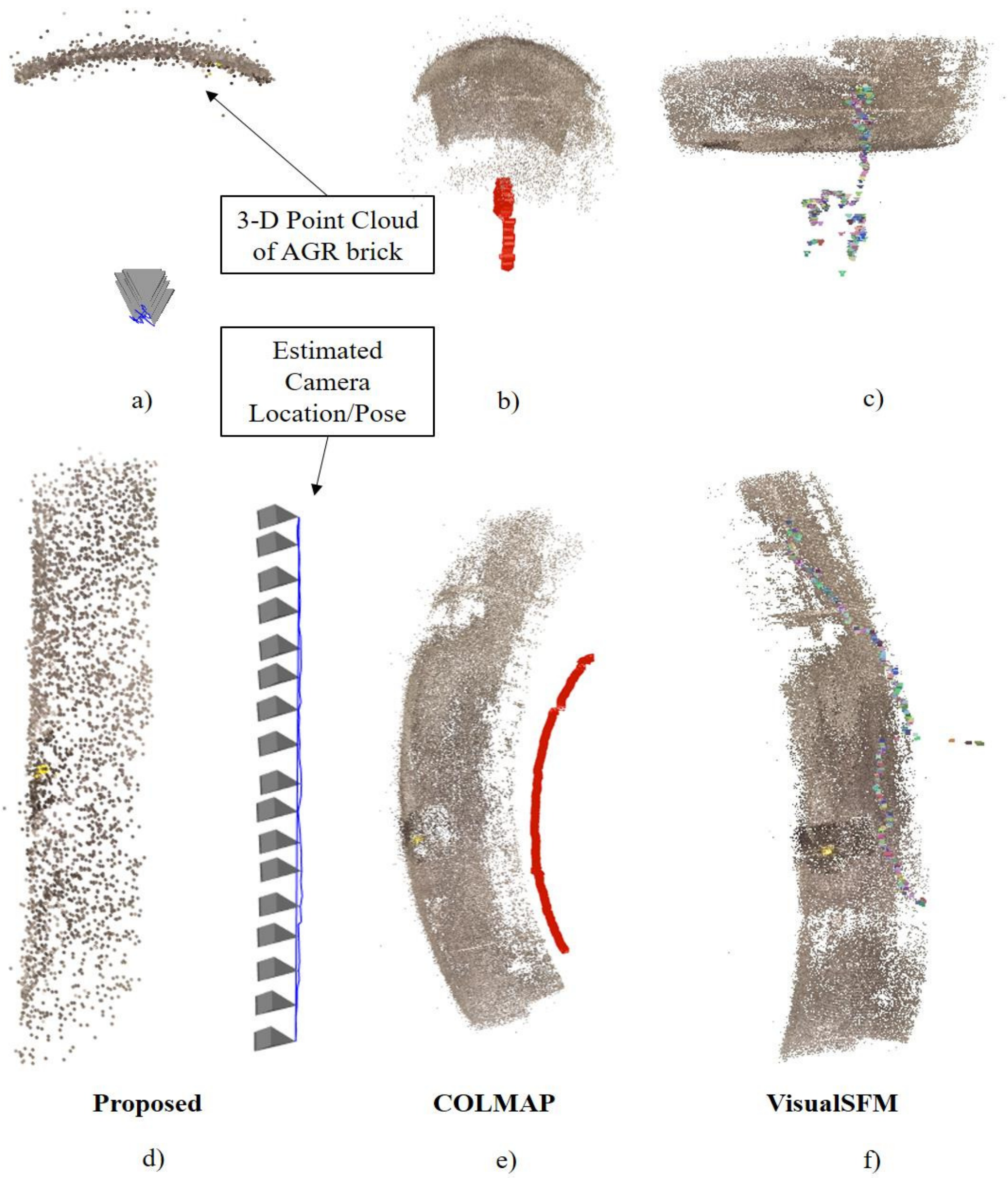


Fig.5. Results obtained using AGR laboratory footage. a-c) Above camera view of the AGR brick point cloud reconstructions with the associated camera trajectory using our reconstruction framework, COLMAP and VisualSFM respectively; d-f) Camera view of a point cloud reconstruction of a scan obtained within a single AGR brick using our reconstruction framework, COLMAP and VisualSFM respectively.

overlay is removed) and to reduce the amount of computation required when producing a 3-D reconstruction. No additional information about the channel or camera calibration data is provided during the reconstruction process to ensure parity with reconstructions generated using the RVI footage.

Evaluation of the reconstruction quality and accuracy is done through a comparative visual analysis between reconstructions obtained using both AGR laboratory footage and RVI inspection footage. Furthermore, we utilize COLMAP [9] and VisualSFM [8], two closed-source end-to-end state-of-the-art incremental reconstruction frameworks to compare reconstruction quality to our own framework using subsets of footage. All reconstructions are applied to the same input image sets and there are no geometric priors or constraints utilized within the reconstruction stage of any tested framework.

4.2 AGR laboratory footage

The footage used for the reconstruction of the AGR brick as seen in Fig.4. comprises of an entire mid-layer

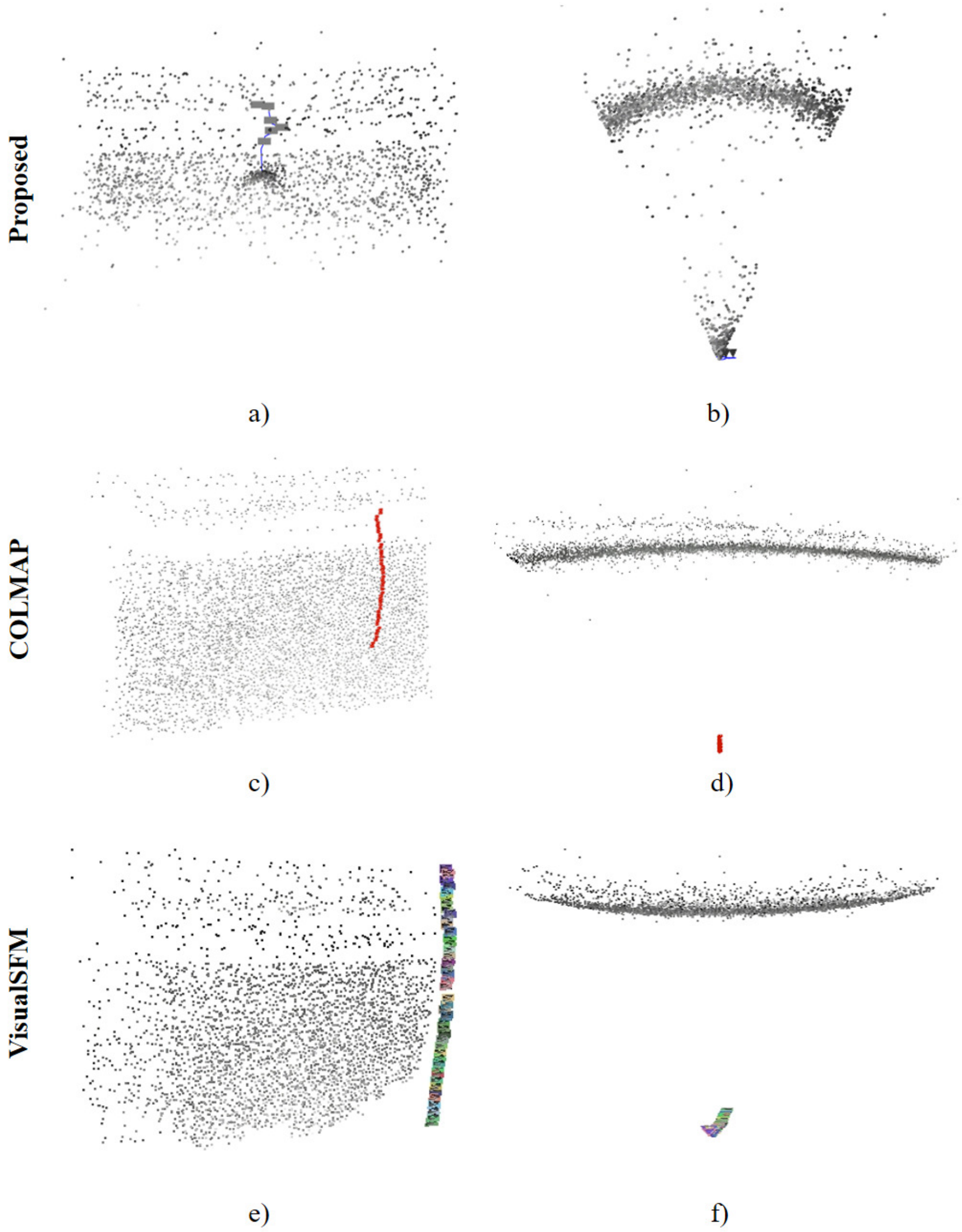


Fig.6. Results obtained using RVI inspection footage of the brick interface as seen in Fig.2b) - a) Reconstruction using our framework from the view of the camera; b) Top down view of reconstruction using our framework. Note the curvature of the brick being picked up correctly; c) Reconstruction from the camera view using COLMAP; d) COLMAP reconstruction from top down view; e) Reconstruction from the camera view using VisualSFM; f) VisualSFM reconstruction viewed from above.

region of a AGR brick which proves a testing benchmark for all evaluated reconstruction frameworks. The resulting sparse point cloud reconstructions are shown in Fig.5. As demonstrated in the COLMAP and VisualSFM reconstructions in Fig.5b-c), the reconstruction frameworks struggle to interpret the curvature of the brick correctly and the point cloud and the corresponding camera trajectory demonstrate a large degree of cumulative drift predominant within incremental systems [9]. This drift is more perceivable from reconstructions using COLMAP and VisualSFM in Fig.5e-f) where the reconstructions from both methods arch forwards and backwards correspondingly. In comparison, the reconstruction provided by our own framework in Fig.5a/d) has minimal positional drift with the camera location correctly following a linear path at a set distance away from the triangulated 3-D points and

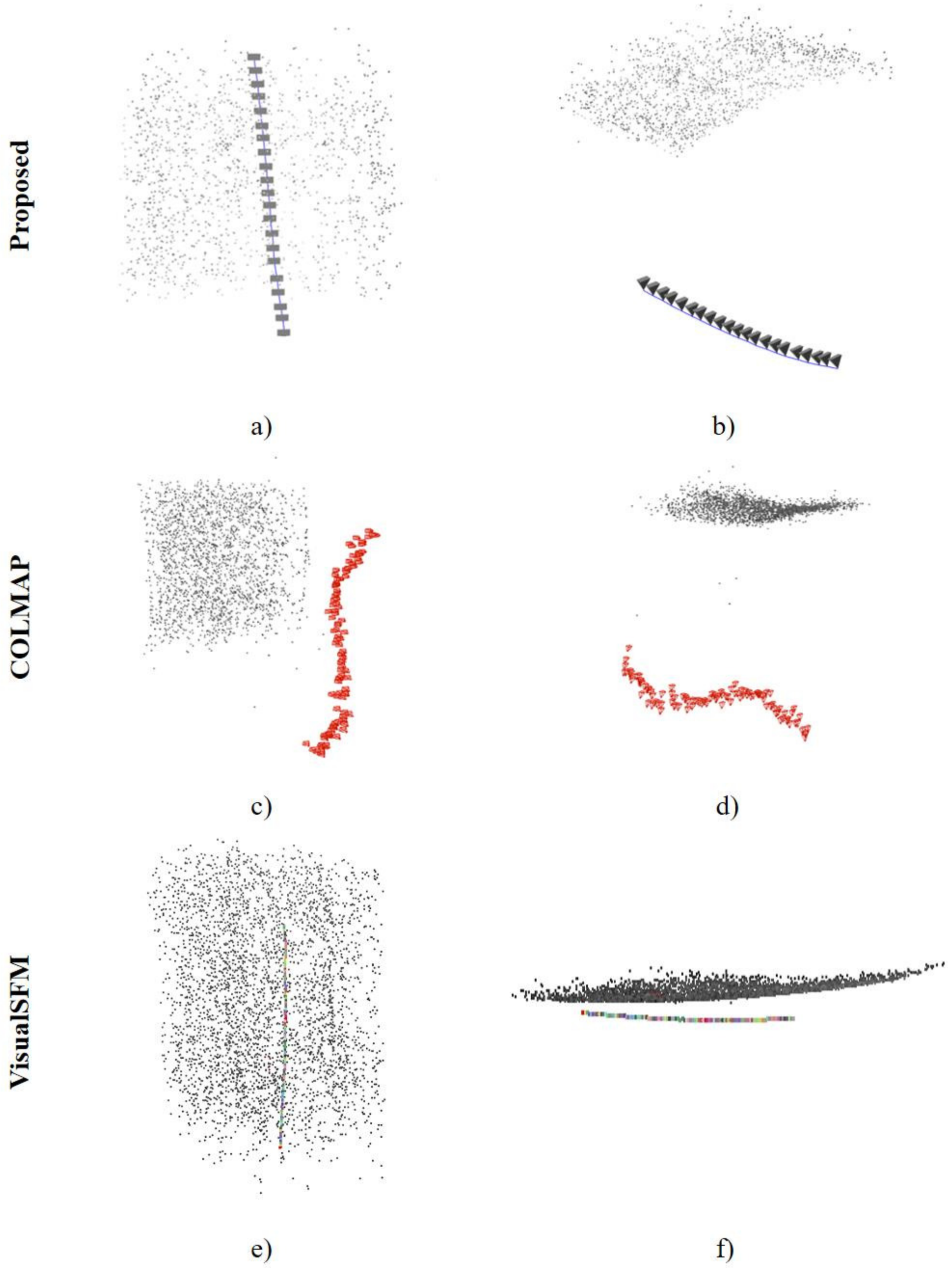


Fig.7. Results obtained using RVI inspection footage of a brick mid-layer as seen in Fig.2c) - a) Reconstruction using our framework from the view of the camera; b) Side view of reconstruction using our framework.; c) Reconstruction from the camera view using COLMAP; d) COLMAP reconstruction from side view. Note the erratic camera trajectory in both COLMAP reconstructions; e) Reconstruction from the camera view using VisualSFM; f) VisualSFM reconstruction viewed from the side.

correctly represents the curvature of the brick. In Fig.5 however, the reconstructions produced by our own work are noticeably sparser with 5494 3-D points while the COLMAP and VisualSFM reconstructions containing 88,289 and 144,331 3-D points respectively. This is due to our framework tracking more reliable and stable feature points across a large number of views whereas COLMAP and VisualSFM inherently have a larger number of false matches at the expense of loss of reconstruction density. This is reflected in the computation time of our framework being 549s whereas VisualSFM and COLMAP took 2307s and 13410s respectively.

4.3 RVI Inspection footage

To evaluate the performance of our proposed approach when applied to real in-core RVI inspection footage, two different image datasets were used to effectively challenge the reconstruction frameworks; the first containing a brick interface (as seen in Fig.2b)) and is inherently symbolic of areas which have a high degree of features and the second being a mid-layer brick region as seen in Fig.2c) where there are very few and in some cases no observable salient features. Since there is no ground truth available for RVI footage, knowledge about the brick structural morphology is utilized from the laboratory footage and the corresponding experimental rig. The reconstruction results generated by all tested frameworks can be viewed in both Fig.6 and Fig.7.

4.3.1 Brick Interface Image Dataset

When applying reconstruction techniques to brick interface images, the COLMAP/VisualSFM reconstruction framework results as seen in Fig.6.c-f) highlight an ability to easily reconstruct a point cloud due to the innate amount of features available across all the images. In Fig.6d) and Fig.6f) nonetheless, it can be observed that both COLMAP and VisualSFM struggle to determine the curvature of the observed brick interface even with a high number of detected features. Furthermore, inaccurate bending of the brick interface correlates to the reconstruction results observed using laboratory footage with said frameworks. In contrast, our proposed reconstruction framework is capable of accurately extracting this curvature of the brick interface at the expense of noisy 3-D points as visualized in Fig.6a) and Fig.6b). The resulting reconstructions contain 2292, 4809 and 3885 3-D points for our own reconstruction framework, COLMAP and VisualSFM respectively with reconstruction times of 53**s**, 101**s** and 68**s**.

4.3.2 Mid-layer Image Dataset

Mid-layer brick reconstructions are significantly more challenging and pose a different type of problem to the brick interface images due to a low contrast and texture of the image which results in a distinct lack of feature correspondences. Consequently, reconstructions demonstrate high degrees of sparsity and this is exhibited in all results in Fig.7. As seen in the reconstructions produced by both COLMAP and VisualSFM in Fig.7c-f), both reconstructions suffer the same bending and do not exhibit the brick curvature observed in Fig.7b) produced by our proposed framework. Furthermore, the resulting camera trajectory in Fig.7c-d) reproduced by the COLMAP framework is erratic whereas the trajectories determined by VisualSFM and our implementation correctly exhibit a smooth vertical motion which is expected. Due to the non-descript nature of mid brick layers, the number of 3D points determined are low; 1706, 2422 and 4319 3D points for our own framework, COLMAP and VisualSFM respectively with reconstruction times of 158**s**, 74**s** and 167**s**.

4.4 Discussion

The SfM framework introduced in this paper is shown to produce representative 3-D reconstructions of the AGR graphite bricks. In contrast, current state-of-the-art incremental reconstruction methods struggle with the low feature space that results in reconstructions that arc and bend inaccurately. By deploying techniques which iteratively search for robust matches using incorporated knowledge motion priors, the feature correspondences within the channel are more reliable and produce more representative reconstructions but come at the expense of point cloud sparsity. Additionally, COLMAP and VisualSFM incorporate a re-triangulation process which allows failed matches to be triangulated with a lower reprojection error threshold. Conversely, this results in unstable and possibly erroneous feature correspondences to be incorporated, possibly resulting in misrepresentative bending of the resultant point clouds.

Additionally, due to the small image datasets, reconstruction times of our own framework match or outperform the performance of COLMAP and VisualSFM which have CPU and GPU accelerated SfM modules. At this time, our implementation does not include these optimizations due to the prototypical nature of this work.

5 Conclusion

We have presented a bespoke SfM framework which can be utilized to generate representative 3-D point clouds of 1) video footage captured under controlled laboratory conditions and 2) real in-core video inspection data captured during routine inspection of AGR fuel channels. The method relies on capturing robust feature correspondences using an iterative knowledge-based approach and is demonstrated to work on both datasets without using any additional information such as camera calibration data. Our proposed framework has been shown to outperform current state-of-the-art incremental reconstruction techniques when applied to AGR inspection footage. The next steps for this work will aim to produce circumferential 3-D reconstructions by incorporating multiple scans together into a singular model, and to create textured 3-D models using Multi-View Stereo (MVS) techniques [9]. Looking to the future, it is anticipated that the 3-D reconstructions produced by our proposed framework could provide inspection engineers with a new way of reliably visualizing the image data captured within the AGR fuel channels.

Acknowledgement

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