

Automatic Image selection in Photogrammetric Multi-view Stereo methods

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ABSTRACT

This paper brings together a team of specialists in optical metrology, museum curation, collection digitization and 3D development to describe and illustrate by example a method for the selection of the most suitable camera views, vantage viewpoints, from a large image dataset intended for metric 3D artefact reconstruction. The presented approach is capable of automatically identifying and processing the most appropriate images from a multi-image photogrammetric network captured by an imaging specialist. The aim is to produce a 3D model suited to a wide range of museum uses, including visitor interactives. The approach combines off-the-shelf imaging equipment with rigorous photogrammetric bundle adjustment and multi-view stereo (MVS), supported by an image selection process that is able to take into account range-related and visibility-related constraints. The paper focusses on the two key steps of image clustering and iterative image selection. The developed method is illustrated by the 3D recording of four ancient Egyptian artefacts from the Petrie Museum of Egyptian Archaeology at UCL, with an analysis taking into account completeness, coordination uncertainty and required number of images. Comparison is made against the baseline of the established CMVS (Clustering Views for Multi-view Stereo), which is a free package for selecting vantage images within a huge image collection. For the museum, key outputs from the 3D recording process are visitor interactives which are built around high quality textured mesh models. The paper therefore considers the quality of the output from each process as input to texture model generation. Results demonstrate that whilst both methods can provide high quality records, our new method, Image Network Designer (IND), can provide a better image selection for MVS than CMVS in terms of coordination uncertainty and completeness of the final model for the museum recording of artefacts. Furthermore, the improvements gained, particularly in model completeness, minimise the significant overhead in mesh editing needed to provide a more direct and economical route to 3D model output.

Keywords: cultural heritage objects, Multi View Stereo (MVS), Structure from Motion (SfM), Close Range Photogrammetry, Imaging Network, Image Clustering and Selection, ancient Egypt, cartonnage, Hawara, Gurob.

1. Introduction

Museums are increasingly exploring the potential of artefact 3D imaging as a means of engaging the public and building digital assets that can facilitate research. Since 2006, the Petrie Museum of Egyptian Archaeology and the UCL Photogrammetry and 3D Imaging Metrology Research Centre, in partnership with Arius 3D Inc., have been involved in a collaborative project which aims to develop a range of digital 3D resources for the recording and interpretation of the museum's collection. While most objects have been imaged using an Arius 3D colour laser scanner, it has been recognized that laser scanning is not suitable for all museum objects. Imaging of very large or small objects, those made from flexible materials, or the recording of the fine details characteristic of material or technology can be problematic.

The condition of the object may also be a critical factor in the choice of imaging technology. Because the gantry-

mounted Arius scanners used for this project have a limited range of movement, fragile objects with complex geometry may need to be repositioned many times for complete image capture and this level of handling may not be appropriate. In these instances, photogrammetry can offer a viable alternative means of 3D image capture but this is only the case if the resulting image dataset is sufficient to enable a suitable 3D model of the object to be constructed. If subsequently the acquired dataset is deemed insufficient (either due to a lack of images from a certain vantage point or because of surface occlusion) or has a high level of geometric inaccuracy, then the museum faces the discouraging prospect of deciding whether to move a very delicate object again in order to obtain the necessary data. From the museum perspective there is therefore a real need for a reliable, efficient photogrammetric image capture procedure which can ensure that the data collected will result in an accurate and visually appealing 3D model.

Today, 3D reconstruction from images using Structure from Motion (SfM) [SSS2006] and Multi View Stereo (MVS) [FP2010] methods is as easy as clicking on a few buttons in a free software package installed on a laptop (e.g. [PHO2012], [INS2012], [CAT2012], [SNA2010], [FP2010]). The ease of use of these packages within the cultural heritage sector can make their uptake tempting. However, there is no certainty that the best images will have been chosen and questions remain as to whether or not the final model is geometrically and colourimetrically accurate and fit for purpose.

This paper discusses development of a new software application, IND (Image Network Designer) which automatically selects the most suitable camera views from a dense set of images captured in the museum photographic studio. The software takes into account all possible range and visibility related constraints, and uses them to construct the 3D model. As trials on four ancient Egyptian objects in the Petrie Museum demonstrate, not only does this give a more efficient process, but the 3D model outcome has visibly better surface completeness and is more accurate, since the software uses the best available images for local reconstruction. The resulting higher quality surface reconstruction can provide a significant improvement in the time and effort needed to produce 3D model outputs that are fit for a wide variety of museum purposes.

2. Background

The photogrammetric MVS workflow for capturing images of cultural heritage artefacts can be outlined as follows: a) Design of the imaging configuration (providing targets, imaging network configuration and sensor selection) [FRA1984],[SFS*2004],[OD2007]; b) Geometric and radiometric calibration of the camera or cameras [RF2006]; c) Capture and removal of geometric distortions from the images [RF2006]; d) Accurate image measurements using SfM methods [SSS2006], [AGV2009], [BTZ1996], [PKG1999], [HM2003], [DTC2004], [NIS2004], [ASS2009]; e) Correct scaling and the improvement of accuracy using a photogrammetric bundle adjustment [ATK2001]; f) Image clustering and selection of images with the best content for reconstruction [FCS*2010]; g) Generation of a dense 3D point cloud with MVS methods (e.g. PMVS) [SCD2006], [FYP2010]; h) Surface reconstruction and rendering [RE2006].

While all of these stages were implemented in the creation of datasets for the four ancient Egyptian artefacts, particular attention was paid to stage (f) since this dominates the processing workload according to the number of images used. Improvements gained at this stage can represent a significant economic benefit per 3D model. Furthermore, our experiences with a variety of available algorithms suggest that existing image clustering and selection methods often fail to select the most suitable images for accurate and complete reconstruction. With regard to stage (a), this software will also be able to inform the initial camera placement network, which will streamline the capture process by eliminating redundant imaging. Progress in this stage of the workflow will be discussed in a future publication.

One of the most relevant pieces of research on the topic of image clustering and selection is presented in CMVS [FCS*2010], which in addition to providing a critical discussion of the previous research in this field, proposed a method which can extract a relevant image dataset from thousands of images downloaded from the internet. Since the method presented is a free open source package, it has been widely adopted by many researchers. Among the problems of CMVS in clustering a large image dataset captured from a cultural heritage object are that it does not take into account occluded surfaces and it also does not address the range-related constraints which affect the texture quality of the final model. Moreover, the CMVS strategy does not guarantee the geometric accuracy of the final model since it does not take into consideration the optimum 3D surface coordinate intersection angles.

Among the recent attempts to design an imaging network suited to 3D reconstruction ([DF2009]; [HWZ*2012]; [AGV2012]), Dunn and Frahm (2009) presented a Next Best View (NBV) planning algorithm which can select imaging vantage points from a set of available views. The method takes into account the localised image texture quality using an initial mesh; and similar to the method presented in [TMD2010], considers the accuracy criterion by aligning each camera view direction perpendicular to the semi-major axes of the 3D error ellipsoid. However, the method does not address range-related constraints addressed in Photogrammetric Imaging Network (PND) (imaging scale, resolution, camera field of view (FoV), depth of field (DoF), number and distribution of points and workspace) cited by [MAS1995] and [SFS*2004] and fails to resolve self-occlusions.

Hoppe et al. (2012) proposed an algorithm to design an imaging network which can provide a complete and accurate 3D model of an architectural façade. The algorithm was designed to reduce the flight-time of a Micro Aerial Vehicle (MAV) by providing a minimum number of key viewpoints based on classifying and minimizing all possible viewpoints located in front of every triangle of a rough mesh surface generated from the building. Although the image clustering in this algorithm can considerably reduce the redundant viewpoints and can overcome some visibility constraints, the distance between each viewpoint and triangle was roughly estimated without considering range-related constraints.

Alsadik et al. (2012) designed a rule-based strategy to find the minimum number of viewpoints within an optimal configuration that would provide sufficient coverage and accuracy for 3D reconstruction of cultural heritage objects. The strategy was tested using dense image configurations for a façade and a statue. SfM techniques, implemented in a video imaging stream software (Boujou) provided a surface mesh. The normal vectors of each triangle in the resultant surface provided the basis for filtering out redundant images in the initial network. In the last step of the method, the imaging network was optimized by exploiting a Matlab implementation of a non-linear optimization technique. While the methodology addressed some of the range-related constraints and tried to select optimal images from the initial image positions, it could not resolve self-occlusions.

3. Methodology

In order to improve image acquisition for 3D artefact reconstruction, a new software application IND (Image Network Designer) was developed on top of existing photogrammetric capability at UCL as part of the principal author's PhD studies. The aim was to extract the optimal image dataset for 3D reconstruction from an organized image dataset that has been systematically captured in a professional photographic studio by moving a camera around the object. The strategy selects key viewpoints for 3D reconstruction and removes redundant images. Selection methodology differs from that presented in [HWZ*2012] by considering: (1) field of view (FoV) as a common constraint between range-related and visibility-related constraints; (2) self-occluded areas and (3) range-related constraints (including depth of field, field of view, resolution and scale constraints). The selected images are then exploited in an MVS routine to produce an accurate, dense and colour-corrected 3D model.

3.1 Image Clustering

Once a low quality mesh of the object has been generated using the SfM output, regarding to provide a relatively homogenous imaging network [AGV2012], a four-zone cone is defined with its apex located on each surface point and an axis laid on the surface point normal (Figure 1). A specific width (20 degrees) is considered as an acceptable viewing angle to each zone of this cone (L_{1-4}). The visibility and range constraints of all viewpoints are then tested for each zone of the cone. Based on this testing, all viewpoints are clustered for each successive surface point.

a) Range-related constraints: In order to check the range constraints for each surface point, the distance between each viewpoint and the surface point is compared with the maximum and minimum permissible ranges. The possible ranges are calculated using the approach considered in [MAS1995] which defines a set of functions describing depth of field, field of view, resolution and image scale constraints. If the calculated distance is located within these cut-off ranges, the viewpoint passes the range constraint.

b) Visibility-related constraints: These constraints are tested for each surface point of the rough mesh by taking

into account the self-occluded area, the field of view of each image and the incidence angle of the view to the surface point normal. A self-occluded area occurs when part of the object surface blocks the line of sight for another underlying area of the object from a specific viewpoint. A point is visible in the image if there are no entities between the camera and the point. In order to check self-occluded constraint, the angle between the ray coming from each camera and the line between the point and any other points (O_{0-1} in Figure 1) is calculated. If this angle is less than a pre-set 1 degree threshold, the viewpoint does not pass the constraint.

(1) Field of view constraint: To make sure the point is located in the field of view of a camera, the angle between the ray coming from each camera to the point and the optical axis of the camera is computed (V in Figure 1). If this angle is less than half of the FoV, the viewpoint passes the FoV constraint.

(2) Incidence angle of the point: The uncertainty in estimating the position of a point primarily depends on the triangulation angle (the smaller the angle, the higher uncertainty). On the other hand, a surface point cannot be distinctly recognized in an image if the camera is located at, or close to, the horizon of the point surface. In order to compensate for these facts, the viewpoints are clustered for each point via calculation of the angle between rays coming from the camera and negative direction of the surface point normal. If a viewpoint satisfies all of the above constraints for a surface point, and it is located in one of the zone of the point cone, the value of the zone will be set to one.

3.2 Image Selection

Having classified the viewpoints in the previous step, they should be reduced to a reasonable number for 3D reconstruction. The process of selecting vantage viewpoints is illustrated in a schematic view in Figure 1. The step-by-step procedure to achieve this goal is as follows:

- a) Determine the number of points visible in each image, taking into account the point zones ($Csum$ in Figure 1).
- b) Find and select the most important image considering the number of imaged points (maximum number in $Csum$ array in Figure 1) and remove the selected image from the candidate viewpoints.

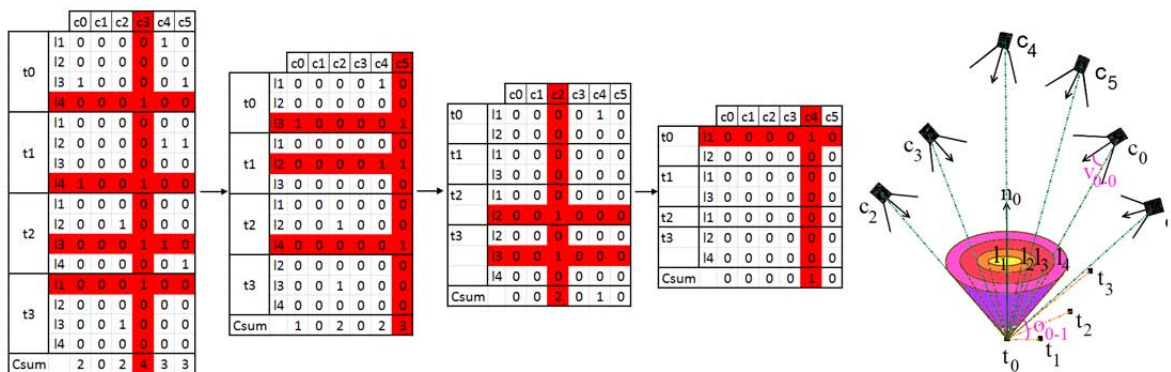


Figure 1: The point cone (right) and a schematic view of clustering and selection steps.

c) Remove the zone of points which was visible in the selected images.

d) Generate photogrammetric image observations for the selected image with a suitable image measurement uncertainty with backward intersection using collinearity equations [LRK*2006].

e) If more than four images are available in the selection, compute a photogrammetric space intersection [LRK*2006]. If not, go to step (a).

f) Compute the number of measured points and their uncertainty. If the uncertainty and completeness criteria, defined below, are not satisfied, but candidate images remain available, repeat from step (a).

As mentioned in step (f), image selection is performed iteratively with stopping constraints based on coordinate uncertainty and completeness:

Coordinate Uncertainty: One of the priorities is to achieve a set of points with a given level of uncertainty. Uncertainty is expressed in relative terms through the r.m.s. (Root Mean Square) uncertainty of the XYZ object point coordinates computed within the network adjustment [ATK2001] divided by the maximum length of the object.

Completeness: As another important factor for 3D reconstruction, the number of measured points is counted and if this number is more than a threshold (90% of all points), this criterion is satisfied.

4. Experiments

To provide high colour quality images for the final model, studio photography with diffused flash lighting was used together with a colour correction process. Two Nikon D700 digital SLR cameras with matching fixed 35 mm focal length lenses were mounted to each other to take advantage of stereo photogrammetry. The stereo vision system was photogrammetrically calibrated with a calibration fixture and a robust bundle adjustment in VMS (Vision Measurement System) which also included estimation of the stereo baseline as a network constraint [SS2001]. Colour calibration images were taken of an X-Rite Mini Color Checker card and processed with X-Rite Passport software to produce colour profiles for the specific camera / lens / lighting combinations used. Adobe

Photoshop CS5 was used to apply the appropriate profile to the raw image files and create sets of TIFF photographs that had colours adjusted to closely match the original objects.

4.1 Photogrammetry of four ancient Egyptian objects

Four ancient Egyptian objects in the Petrie Museum were selected for photogrammetry (Figure 2). The first was the preserved front surface of a mummy head cover (UC79377) dating to the first century AD. The head cover was found by Petrie, probably during his 1888 excavations at Hawara. It had been discovered badly damaged, with the face crushed, and had been kept in storage since its discovery. Following a recent decision to display the object, the museum commissioned conservation treatment of the head cover including restoration of the face. To record this process, photogrammetric surveys were carried out during and after the conservation treatment. The aim was to create 3D interactive allowing visitors to explore the restoration of the face as a result of the treatment. Because the head cover, made of cartonnage (linen strips stuck together with adhesive and bulked with plant fibre, coated with gesso, and then painted and gilded) was very fragile, handling had to be kept to a minimum. Studio photography was therefore carried out with the head cover kept flat and imaged only on its primary decorated surface.

The next two pieces were fragments of the same cartonnage foot cover, which again would have originally been placed over a wrapped mummy (UC28120, right foot; UC45967, left foot). Of similar provenance and date to the head cover, these were found in the museum in two different storage locations. The museum wanted to join the two fragments virtually and create an interactive allowing the public to do the same. The photogrammetric survey therefore had to provide accurate geometry which would allow the two fragments to be reunited using their 3D images. Again, fragility of these pieces was an issue.

The final object is a limestone stela (UC14386) from the site of Gurob and probably dating to the time of the 19th Dynasty (around 1292-1185 BC), showing an official worshipping a figure of the deified king, Thutmose III. Here, the intention was to try to capture the carved decoration in as much detail as possible.



Figure 2: Images showing the head cover (UC79377), right foot of the foot cover (UC28120), left foot of the foot cover (UC45967) and stela (UC14386) during the photogrammetric imaging campaign.

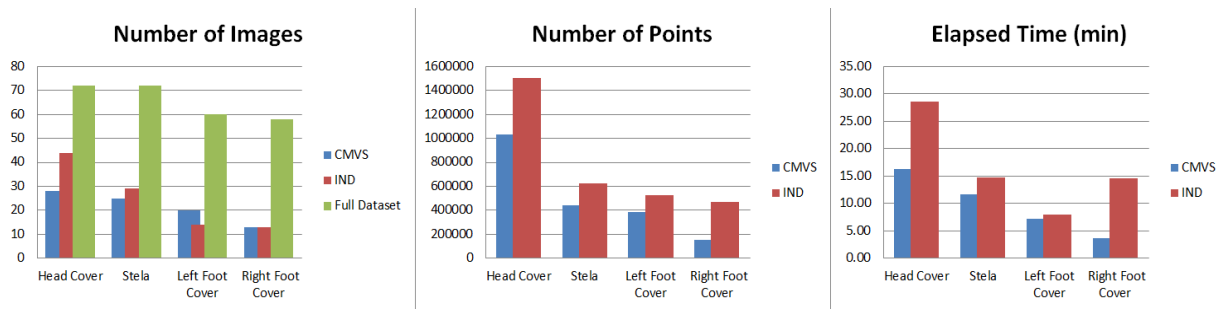


Figure 3: Comparing CMVS and IND from different aspects (number of images, number of reconstructed points, elapsed time).

Studio photography was carried out following an established UCL procedure. Each object, except the head cover, was photographed on both sides by placing it on a pre-produced calibrated black board equipped with coded photogrammetric targets. The coordinates of the 30 coded targets were accurately determined using a network of images taken with a Nikon D700 SLR camera processed with a self-calibrating bundle adjustment. Scale for the solution was provided by including a calibration object and Brunson scale bar within the field of view in place of the object.

Images were captured in curved paths around the object at regular distances between each exposure station and a standoff from the object surface of 70 cm. The physical focus and focal length of the lens were fixed to provide constant interior camera geometry. After colour correction of the photographs, they were geometrically undistorted according to the interior camera parameters established by calibration. The undistorted images were processed in Bundler, an open source SfM package, in order to automatically generate an initial sparse set of image observations and 3D coordinates. These data were then imported into a photogrammetric bundle adjustment (VMS) that supports a comprehensive camera geometry model, along with the use of coded target control information. This improved the uncertainty and accuracy of the solution. The exterior orientation parameters determined through bundle adjustment were then input both CMVS and the method presented in this paper (shown as IND in Figures 3, 4, 5, 6) in order to cluster and select key viewpoints. Finally, dense point clouds, with sub-millimeter point spacing, were obtained with PMVS.

4.2 Comparing CMVS and IND for image clustering and selection

The CMVS and IND methods were compared (Figure 3) according to five criteria:

Mean RMS Uncertainty of Surface Point Coordinates (μm)

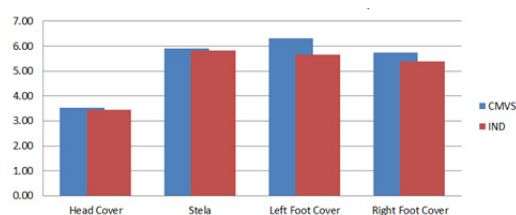


Figure 4: Uncertainty comparison between IND and CMVS.

a) **Number of images** selected by each method out of the total available for each data set.

b) **Number of points** generated by each method after processing with PMVS.

c) **Elapsed time** required to complete the PMVS process given the selected image set. The PMVS process consists of reading images, adding seed points, expanding, filtering and storing the final point clouds.

d) **Mean uncertainty of point coordinates** expressed in microns (μm) as the mean RMS of all X,Y,Z surface point coordinates estimated within the VMS photogrammetric bundle adjustment (Figure 4).

e) **Network geometry of the clustered images.** This is shown in Figure 5 highlighting differences between the IND and CMVS selections versus the full data set.

In our tests thus far, IND provided better image datasets for MVS in terms of the number of points and uncertainty in all datasets. For example, PMVS could generate more points for the left foot covers using the IND dataset (523,418 pts.) than the CMVS dataset (382,480 pts.), while the number of images in IND dataset (14) was fewer than CMVS (20) and the elapsed time for both datasets was almost identical (around 8 minutes on an 8 core Intel(R) Xeon(R) CPU X5472 @ 3.00GHz with 64 GB RAM).

Moreover, testing the uncertainty in VMS shows marginally better values for IND. This improvement is attributable to IND selecting images that have the greatest object coverage as evidenced in all datasets where IND has included significantly more images from the upper ring of images. From a photogrammetric standpoint, these images provide maximum overlap across the imaging network and therefore promote measurement redundancy.

For the geometrically more complex head cover and stela datasets, more images were selected by IND than CMVS. A specific surface area around the head cover's face was important for full reconstruction; six images in a specific curve path had been captured for this area and were expected to be used in the dense reconstruction procedure. CMVS selected only two of them, while IND automatically chose five images considering the occlusions in this area. Even difficult but important geometries for interpretation and visualisation, like the thin edges of the head cover, could be reconstructed with datasets provided with IND which logically selected the vantage images in these datasets.

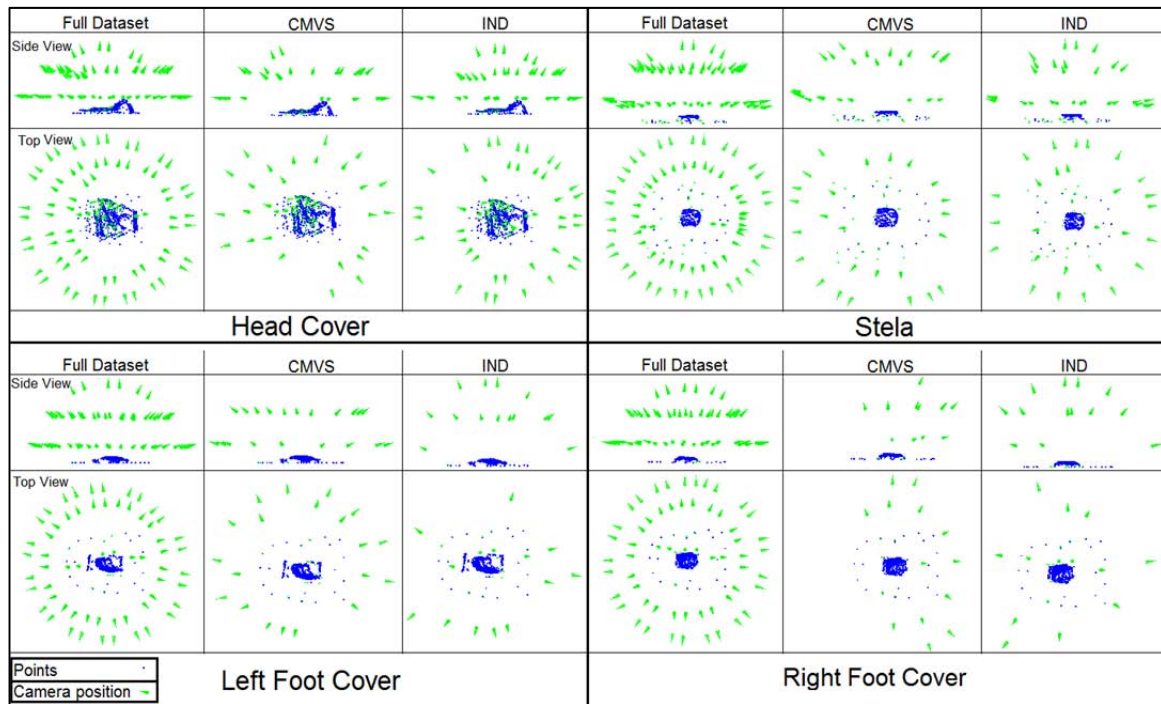


Figure 5: The imaging network in the four datasets in complete mode, generated with IND and CMVS.

To determine the potential impact of these improvements for the development of museum visitor interactives, the IND and CMVS point cloud models were re-meshed in a commercial software tool [GEO2012], which is currently being used by the Petrie Museum for its on-going development of game design-based interactives [UNI2012]. As Figure 7 indicates, the surface produced from the IND point cloud shows visibly better coverage than the CMVS dataset, where a number of substantial holes can be seen. Not only would these holes require time consuming manual processing but, from the museum perspective, their substantial size also introduces a degree of ambiguity regarding the accuracy of the reconstruction.

Going forward, further imaging research based on ancient Egyptian objects in the Petrie collection is now underway or planned. For the head cover, it is anticipated that a comparative study of the datasets from the two photogrammetry sessions, and their integration into museum interactive, will be published. The stela is suitable for laser scanning and this may be done in the future as part of a critical comparison of the two techniques. While the fragile condition of the head cover has meant that only the remaining upper surface could be imaged, we are currently using the datasets from the other three objects to allow us to explore the application of the IND software to imaging in the round.

5. Conclusions

This paper describes a significant advance in the selection of the most suitable camera views from a large image dataset intended for 3D object reconstruction. As we demonstrate, by taking advantage of both the Photogrammetric Imaging Network (PIN) and Next Best

View planning (NBV) methods in the IND package, considerable improvements were made in the selection and clustering of the most useful images in the datasets of four ancient Egyptian artefacts. In particular, the results show the advantages of IND in comparison with CMVS, which is a well-known and widely used package for 3D imaging. The next step of this research will be to present a strategy for automatically designing an optimal imaging network which identifies the best camera positions for image capture around an artefact. This will reduce the number of photographs required for the model while ensuring optimal surface coverage. The potential benefits for the cultural heritage sector and for the development of visitor interactives are a more efficient image capture process, which can reduce the movement and handling of an object, and greater confidence that the resulting model will be accurate and fit for purpose.

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Figure 6: Point cloud comparison between IND and CMVS approaches for the head cover.

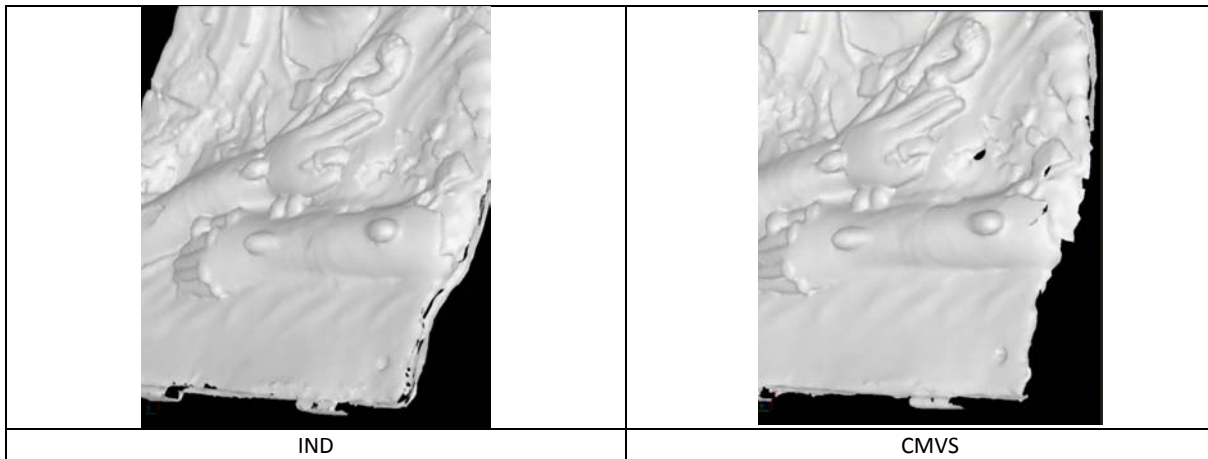


Figure 7: Re-meshed surface from IND and CMVS as used for UCL Petrie Museum visitor interactives.