Using Nonoptimal or Archival Photographs for Constructing 3D Models

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Abstract

Photogrammetry is well on its way to becoming a standard part of archaeology. As helpful as new technology can be, it is not always applicable to past excavations. We recommend following best practices for all current work, but photographs from prior excavations are generally not ideal for photogrammetry. We demonstrate the utility of photogrammetry under various, problematic conditions using test cases from three archaeological sites excavated between the 1930s and the current decade. We discuss some of the successes, challenges, and conditions where we succeeded or failed to create a viable 3D model. Our results indicate that successful and accurate 3D models can be created from excavation photographs taken under a variety of circumstances and without accompanying camera metadata. The major limiting factor we found was lack of overlapping coverage of the subject, which proved problematic to a greater or lesser degree in all of our case studies.

Keywords: Photogrammetry, archival images, 3D models

Introduction

Structure from motion (SfM) is a branch of photogrammetry used to create 3D structure from 2D photographs. In common usage, the term "photogrammetry" usually refers to SfM, and we follow this convention. Photogrammetry is well on its way to becoming a standard part of archaeology. As helpful as new technology can be, it is not always applicable to past excavations. We recommend following best practices for all current work, but photographs from prior excavations are generally not ideal for photogrammetry. Our purpose in this paper is to explore what can be done with photogrammetry under problematic conditions using photographs taken from several years to decades in the past. This has been called historical, archival, or retrospective photogrammetry (Wallace 2017).

A major challenge for this type of photogrammetry is assessing the accuracy of the 3D model. The best method is to compare the photogrammetry model to a model collected via a laser scanner (e.g., Skarlatos & Kiparissi 2012). Accuracy can also be compared to measurements taken directly from an artifact or feature. To determine accuracy, we compared a 3D model obtained via a laser scanner with a photogrammetry model generated from non-optimal photographs. In this paper, we discuss some of the successes, challenges, and conditions where we succeeded or failed to create a viable 3D model. Our results indicate that successful and accurate 3D models can be created from excavation photographs taken under a variety of circumstances and without accompanying camera metadata. The major limiting factor we found was lack of overlapping coverage of the subject, which proved problematic to a greater or lesser degree in all of our case studies.

Most of the models in this study were created with Agisoft PhotoScan Standard (2018; version 1.4.1), which is widely used, inexpensive, and relatively user friendly. Thus, creating 3D models from archival or nonoptimal photographs can be done with little ex-

pense or training. Prior studies in various fields have used historical photographs with satisfactory results. Several studies have used archived aerial imagery for generating photogrammetric 3D models (e.g., Bakker & Lane 2017; Mölg & Bolch 2017; Papworth et al. 2016; Peterson, Klein & Steward 2015; Sevara et al. 2018), and others have successfully used archival photographs for terrestrial photogrammetry (e.g., Bitelli et al. 2017; Falkingham, Bates & Farlow 2014; Grun, Remondino & Zhang 2004; Ioannides et al. 2013; Lallensack et al. 2015; Maiwald et al. 2017; Snavely, Seitz & Szeliski 2008; Wallace 2017). These projects, along with our test cases discussed here, demonstrate the feasibility of creating 3D models using photographs not intended for, or optimal for, use in photogrammetry.

We have modelled four structures at three sites in the U.S. Southwest, all in the state of Utah (see Figure 1). We first discuss the methods used to create the 3D models and some common challenges. We then discuss the results for each 3D model we created by site. We end by summarizing our findings and recommendations.

Figure 1. Map showing locations of sites used in the case studies.

Methods

As previously mentioned, Agisoft Photoscan was used to create the 3D models from the selected photographs. While some details are specific only to Photoscan, the general principles are likely applicable to other software, although Wallace (2017: 614) notes that Photoscan has features often better suited for what he calls "retrospective photogrammetry" than some other software. While we attempted to create one model using the professional version, all the successful models were created using the standard version. The cost is significantly lower, which reduces the price barrier for photogrammetry. The primary benefit, in this case, for using the professional version is the ability to manually place tie points or markers on photographs to assist the software in tying photographs together (see Wallace 2017). While this can be helpful in many situations, it is encouraging that we were able to achieve satisfactory results without the added hassle of manually adding tie points. Eliminating this step speeds the process, although overall this can be a time consuming endeavor. This artic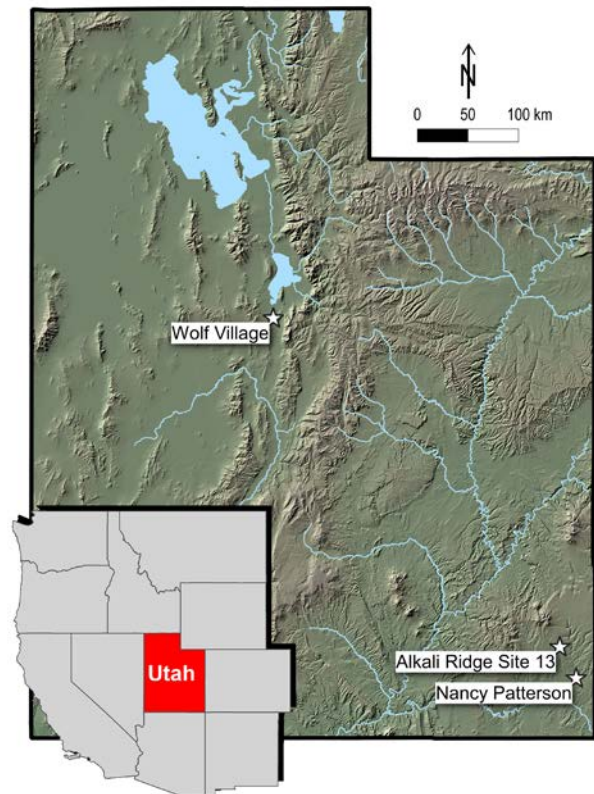le is not a photogrammetry tutorial and is not intended to instruct a beginner, rather, we highlight the additional steps we took and challenges we encountered to achieve results using problematic photographs. While we explain some options specific to Photoscan, we will not discuss each option in detail. Our intent is to encourage others to attempt photogrammetry in similar situations and to share some methods we found helpful.

Photograph Selection

The first step in photogrammetry is to acquire an image set. Generally, more photographs are better than fewer, but with some qualifications. Some difficulty is experienced when photographs were taken at different scales (i.e., close ups with long-distance overviews), but also when there are duplicate or near duplicate photographs and insufficient overlap for other photographs (see Wallace 2017: 611). In the latter case the software may only align the duplicate photographs and ignore other photographs. These issues can be solved by removing the problematic photographs. Our examples do not deal with photographs taken under different lighting and other con-
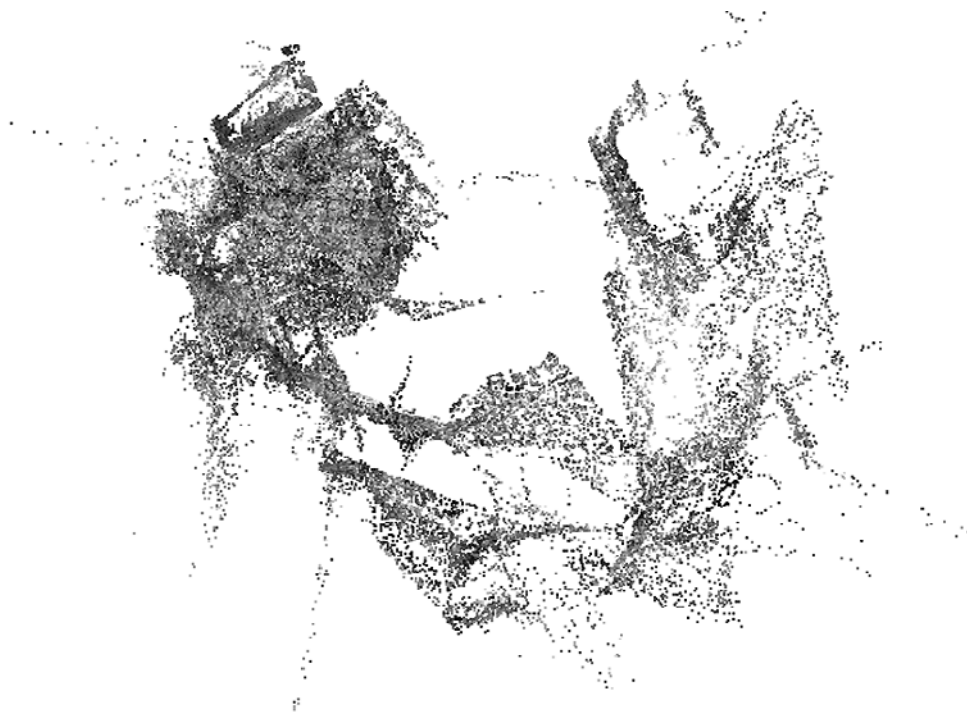
Figure 2. Demonstration of an initial, failed camera alignment in Agisoft Photoscan.

ditions, but using photographs taken with the same lighting, etc., is recommended. We did not have major issues using photographs that had people and objects inconsistently placed. These undesired inclusions can be masked, but we found success by merely ignoring them.

Camera Alignment

The greatest challenge we found is aligning cameras. Once accomplished, generating the 3D model is usually unproblematic, as long as a sufficient number of photographs were aligned. Camera alignment is usually automatic for good photographs, but difficulties occur when the photographs were not captured with appropriate equipment or settings. The primary cause of failed camera alignment is often insufficient coverage. Multiple camera angles are necessary for 3D construction, and the software frequently has difficulty aligning photographs taken at widely different scales. Unfortunately, this situation usually cannot be improved in the circumstances we consider here, as the opportunity to collect more photographs is generally not an option using archival photographs. If overlap is sufficient for a 3D model, which is often only determined after trial and error, then usually some photographs will align correctly, while others (sometimes most) of the photographs will either not

be aligned or will be misaligned. The critical advice at this point in the process is to not become discouraged and to continue working with the photographs to create a proper alignment. The first step is to attempt alignment using multiple alignment configurations. What follows is a mostly nontechnical exploration of the various options related to camera alignment in Photoscan software, and which settings we recommend based on our experience and trials.

Photoscan has several available options, and the highest possible settings are not always best. The primary setting for camera alignment is called "Accuracy." We generally start with high, which uses the photographs at their original scale. The highest setting upscales the photograph by 4, while the medium setting downscales the photograph by a factor of 4. We do not recommend settings below medium. We find that high usually works best, but in some situations the highest or medium settings have provided better results. "Pair preselection" can speed up the alignment process. Typically, we do not select this option, but occasionally we have found better results with this option selected. We usually leave the key point tie limit at the default value, as we have found little difference when changing this value. We often obtain best results with the "Tie point limit" set to zero, which, in this case, means there is no limit to how many points are used to tie photographs togeth-
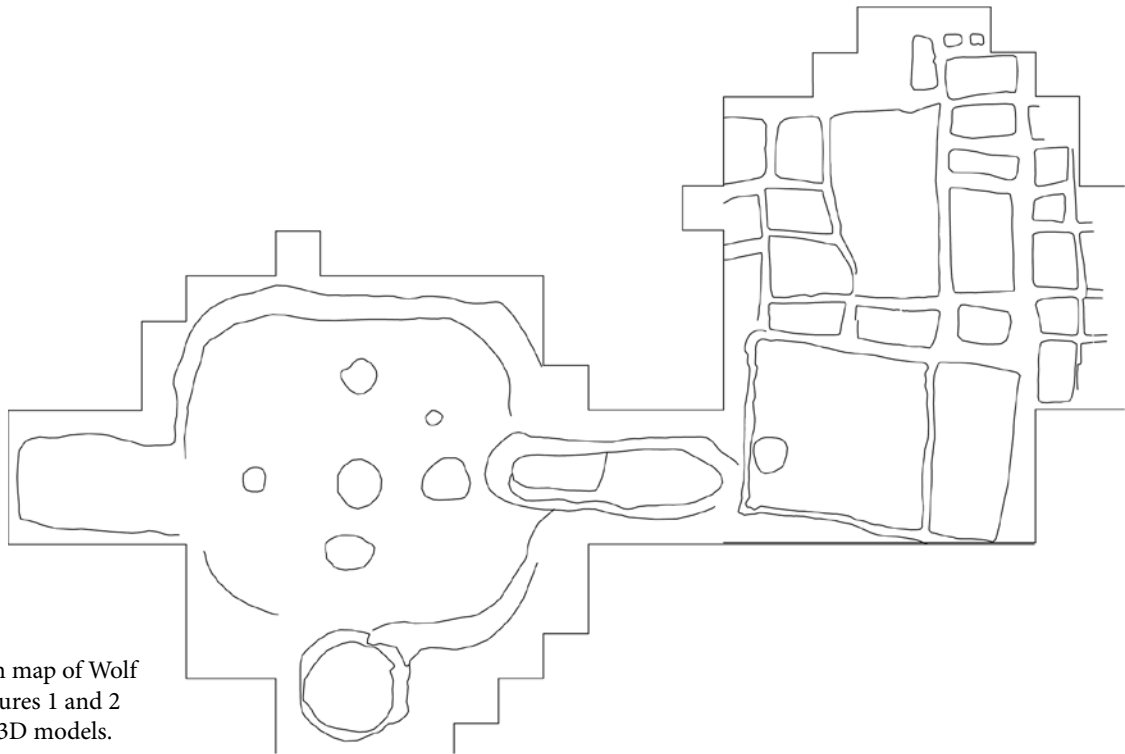
Figure 3. Plan map of Wolf Village Structures 1 and 2 used to align 3D models.

er. Using infinite tie points increases the processing time but not significantly so. Masks can be applied to remove people, objects, or scenery that are not meant to become part of the 3D model, however, we were often able to obtain good results without masking any parts of the photographs, even with people and objects variously placed within the photographs. Masking can become quite time consuming and it is easier to avoid this step when possible. The last option for camera alignment is "Adaptive camera model fitting," which concerns the automatic selection of camera parameters. We recommend leaving this unchecked to start, but selecting this option can sometimes improve results. The best advice we can give for these settings is to patiently experiment with your dataset and determine which settings result in the best possible camera alignment.

Often, some photographs cannot be aligned, and in the case of Figure 2 many photographs are clearly misaligned. We have found great success manually resetting camera alignments. Photoscan has several useful features to aid in this endeavor. Points that are clearly out of alignment can be selected to determine which photographs are causing the problem and can be reset and realigned. A common problem is the misalignment of axes. For example, several models we created resulted in the expected horizontal axis, but some of the photographs were misaligned resulting in

one or more axes lying on different planes (see Wallace 2017: 613–614). Our recommendation is to reset all poorly aligned cameras until all aligned cameras are correctly positioned and the remaining geometry accurately represents the subject. Once accomplished, the problem photographs may be realigned manually one at a time or a few at a time. If the realigned camera causes too much noise, or stubbornly refuses to align properly, then it is best to remove it. One option to further correct this issue is to use manual tie points in the professional edition of Photoscan. But we were able to obtain good camera alignments for each model without resorting to this more time-consuming method. Figure 2 demonstrates the initial camera alignment for a structure discussed later. These alignment results are not promising; however, accurate geometry was captured after attempting multiple alignment configurations and manually aligning photographs. The remainder of the process typically follows standard photogrammetry procedure and does not need to be discussed here.

Scale, Rotation, and Alignment

Often, 3D models must be manually scaled to allow measurement of the model. If models must be combined, as is done in two of the case studies, then the models must not only be scaled appropriately to each
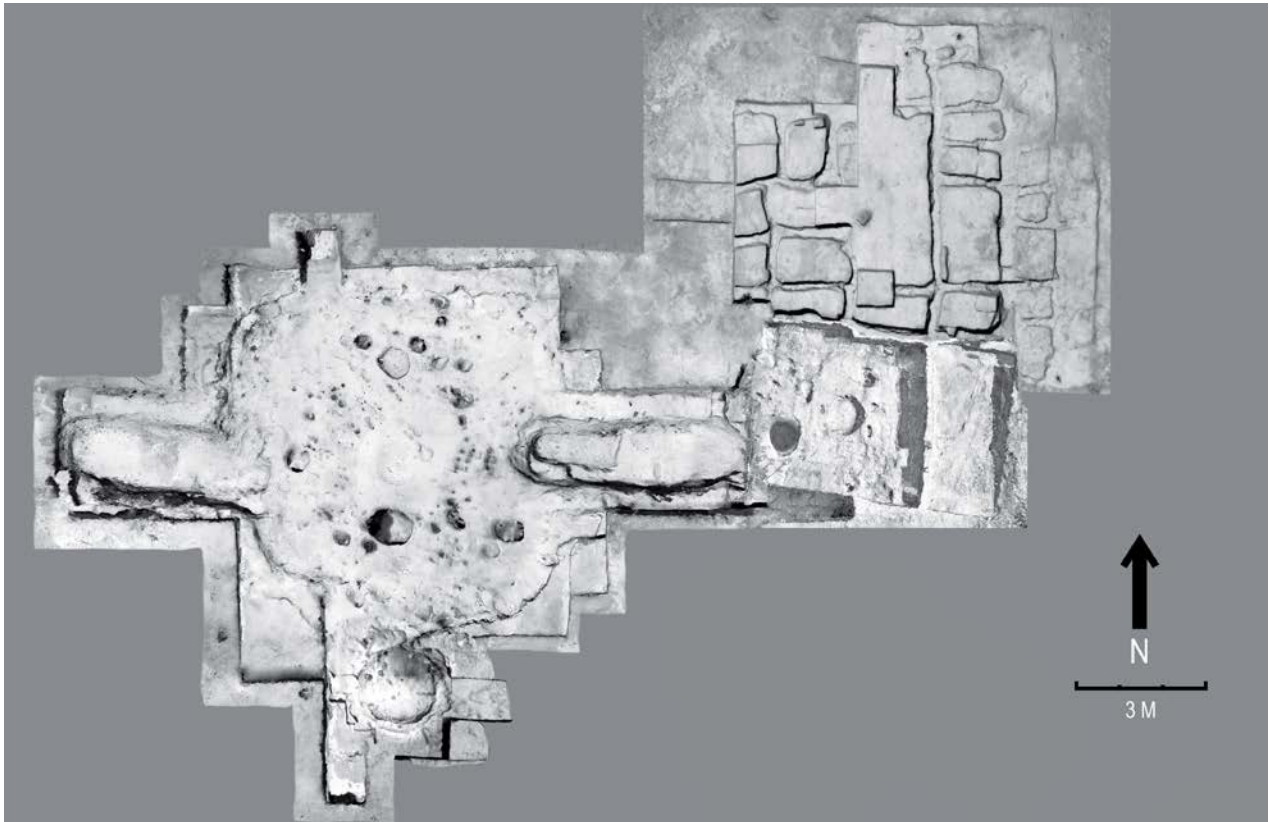
Figure 4. Render of aligned 3D models for Wolf Village Structures 1 and 2. This model uses photographs from 2012 for the main part of the structure on the left and photographs from 2013 for the antechamber at the south end of the structure. Photographs of the main two rooms of the structure on the right were taken in 2010, while the photographs for the cluster of small rooms to the north were taken via an unmanned aerial vehicle in 2016.

other, but must also be aligned, rotated, and positioned appropriately. The open source software Blender (2018; version 2.78) was used for these purposes. Blender offers a full suite of 3D modelling tools but has a relatively high learning curve. A full description of the processes used to scale and orient the models is beyond the scope of this paper; however, a few notes on scaling and alignment are germane. The 3D models created in Photoscan lack a true scale. An object or portion of the 3D model may have a known length, such as a scale reconstructed in the model, and this can be used to scale the entire model. Plan maps can also be used where available. We found using plan maps was the most effective method for our situation. The basic process is to add the plan map to Blender as a background photo, scale the photograph using the scale included in the plan map, and then scale the object itself to align with the plan map. This also worked well for aligning multiple models. Figure 3 shows the plan map for both Structures 1 and 2 at Wolf Village (see case study below), which are adjacent. Figure 4 is composed of four 3D models that were aligned us-

ing the combined plan map for the structures. Blender was also used to render 2D images of the 3D models. Photographs can be rendered with perspective or as orthophotos, which is particularly useful for archaeological applications. Automatic alignment can also be used. The open source software CloudCompare (2016; version 2.7) and Meshlab (Cignoni et al. 2008, Meshlab 2016; version 2016) both have automatic alignment options, but these options require more identical features in the 3D models than we had in our models. Determining the accuracy of the 3D models is a principal concern. The Wolf Village case study will demonstrate the accuracy of one of the photogrammetry 3D models compared to a 3D model created via laser scanner.

Accuracy Comparison

Perhaps the best method to determine the accuracy of these models is to compare the model to a model of known accuracy. In the case of Structure 2 at Wolf Village, we are fortunate to have laser scan data
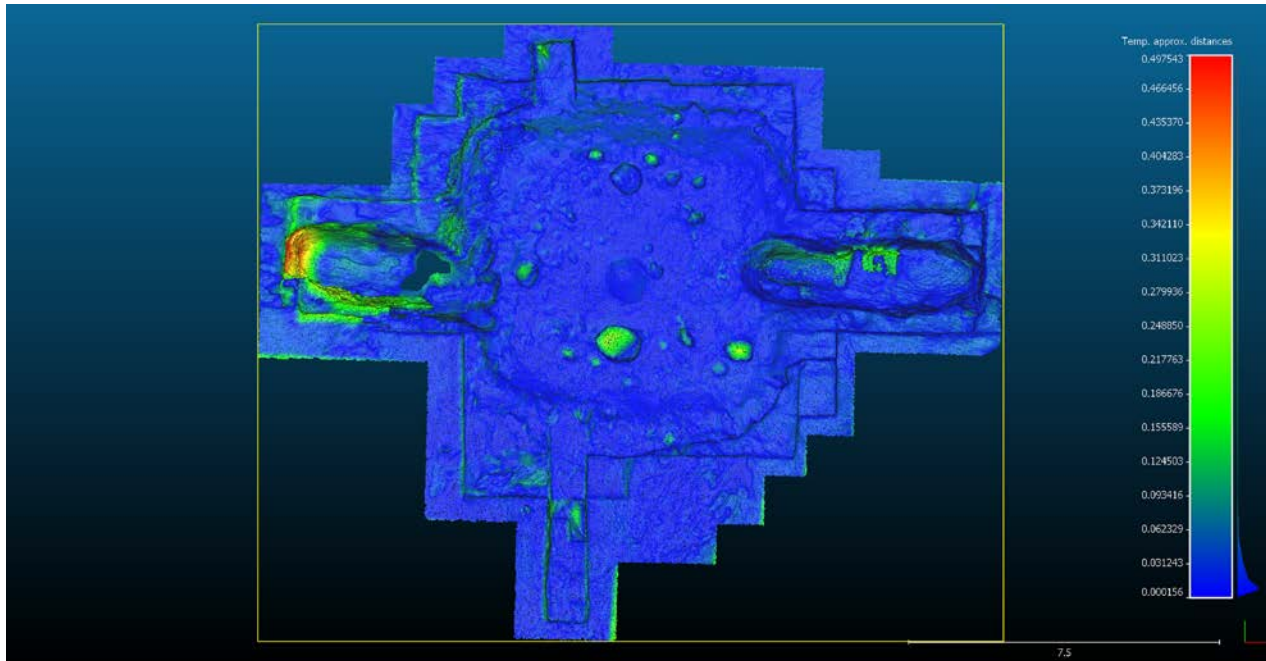
Figure 5. Cloud to cloud comparison between the laser scan and the photogrammetry 3D models of Wolf Village Structure 2.

captured by Brigham Young University staff archaeologist Scott Ure at approximately the same time as the photographs used for photogrammetry. The laser scanner is a FARO Focus 3D 120 with ±2 mm accuracy. CloudCompare was used to compare the models. The mesh models were converted to point clouds and aligned and registered. The cloud to cloud comparison was used to determine the distance between the two point clouds. The result, Figure 5, shows the aligned point clouds and their differences. The western tunnel of this structure has the greatest variation, while many of the subsurface features are not well matched. Figure 6 shows a comparison for the west tunnel between the photogrammetry version, the laser version, and an excavation photograph used in the photogrammetry that was taken at approximately the same time as the laser scan. From these views, the photogrammetry model may best represent the physical structure of the tunnel. Overall, we found the accuracy of the photogrammetry to be at least comparable to the laser scan model.

Case Studies

We have modelled four structures at three sites in the U.S. Southwest, all in the state of Utah. The sites are Wolf Village, Alkali Ridge Site 13, and Nancy Patter-

son Village. All photographs from Wolf Village and all the photographs for the successful 3D model from Alkali Ridge Site 13 were taken using digital cameras with accompanying metadata. The photographs used in the failed reconstruction from Alkali Ridge Site 13 and the Nancy Patterson site were taken with film cameras and were scanned from negatives or from prints. While the use of scanned photographs vs digital provides different challenges for 3D modelling, several challenges were common for all of the models.

Wolf Village

The first site we created 3D models from is Wolf Village, a Native American farming village in the northern part of the state of Utah that dates primarily to the AD 1000s and early 1100s (Johansson, Richards & Allison 2014). The 3D modelling focused on two unusually large structures at the site, Structures 1 and 2. Structure 1 was a multi-room earthen surface structure. Two relatively well-constructed rooms were excavated during the 2009 and 2010 field seasons. In 2013 and 2016, approximately 20 more small rooms were excavated, attached to the north side of the first two excavated. These small rooms were apparently later additions to the structure, as the walls were built on fill that rested against the north wall of
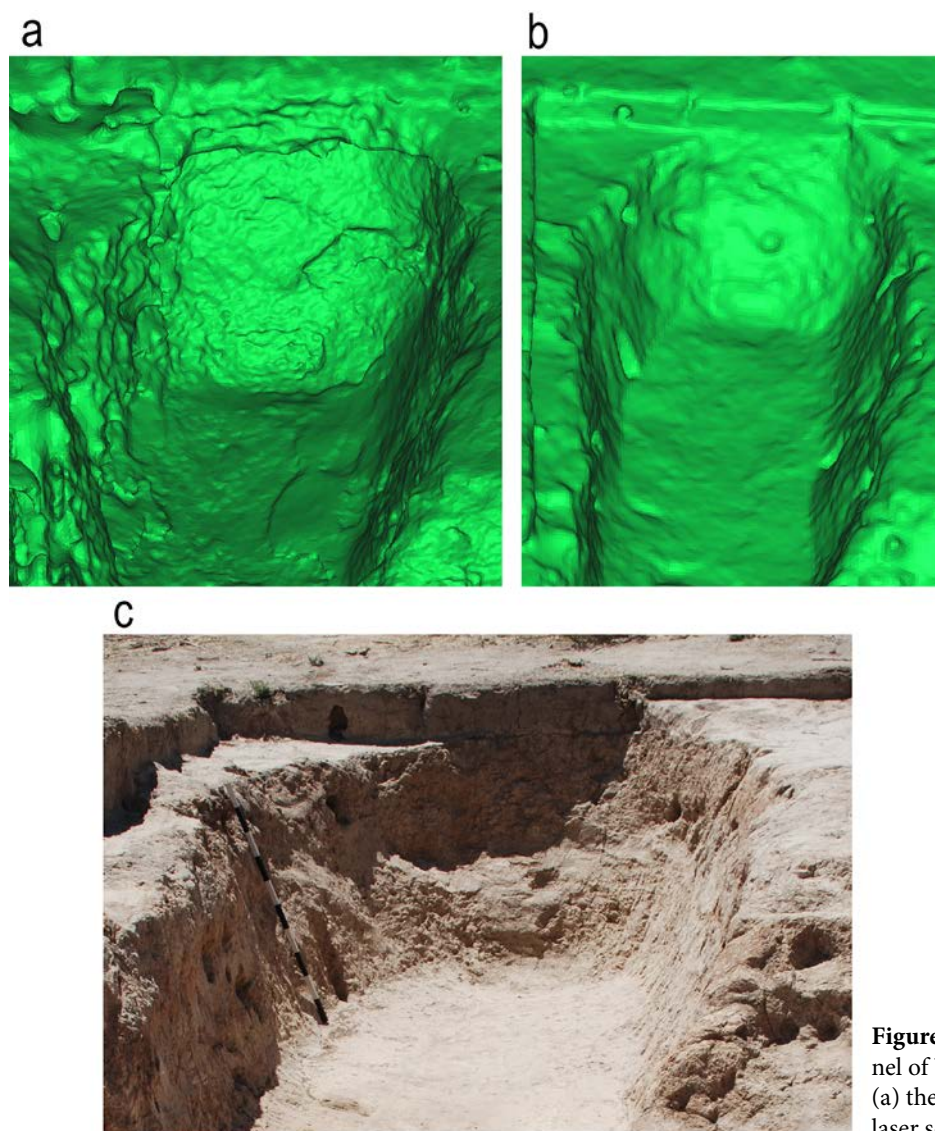
Figure 6. Comparison of the west tunnel of Wolf Village Structure 2 between (a) the photogrammetry model, (b) the laser scan, and (c) an excavation photo.

the first two rooms excavated. In addition to being smaller, the walls of these rooms were thin and poorly built, and floors were difficult to discern. These smaller rooms may have been used for storage, but there is little evidence that they were used at all, and one interpretation is that they were added simply to increase the size and impressiveness of the building.

Just west of the surface structure was Structure 2, a large pit structure totaling 80 square meters, including two large deep tunnels that appear to be entrances as well as a small antechamber on its southern edge. The structure was found at the end of the 2010 field season, then most of it was excavated in 2011 and 2012, although the southern antechamber was not excavated until 2013.

Because the excavation of these two structures was spread over six different field seasons, neither structure was ever completely uncovered at once, nor were major parts of the two adjacent structures open at the same time. Our original intent was to create a 3D model of Structure 2 that included the antechamber excavated the year following the excavation of the main part of the structure and to show this structure's close association with Structure 1. All structures were backfilled for preservation purposes at the end of each season, and it was impractical to remove the backfill each year. The creation of 3D models allowed us to combine models created from photographs taken in different years to show all completed excavations from these structures in one model.

The challenges we faced in creating these models were that these photographs were not intended for photogrammetry and were taken with a telephoto
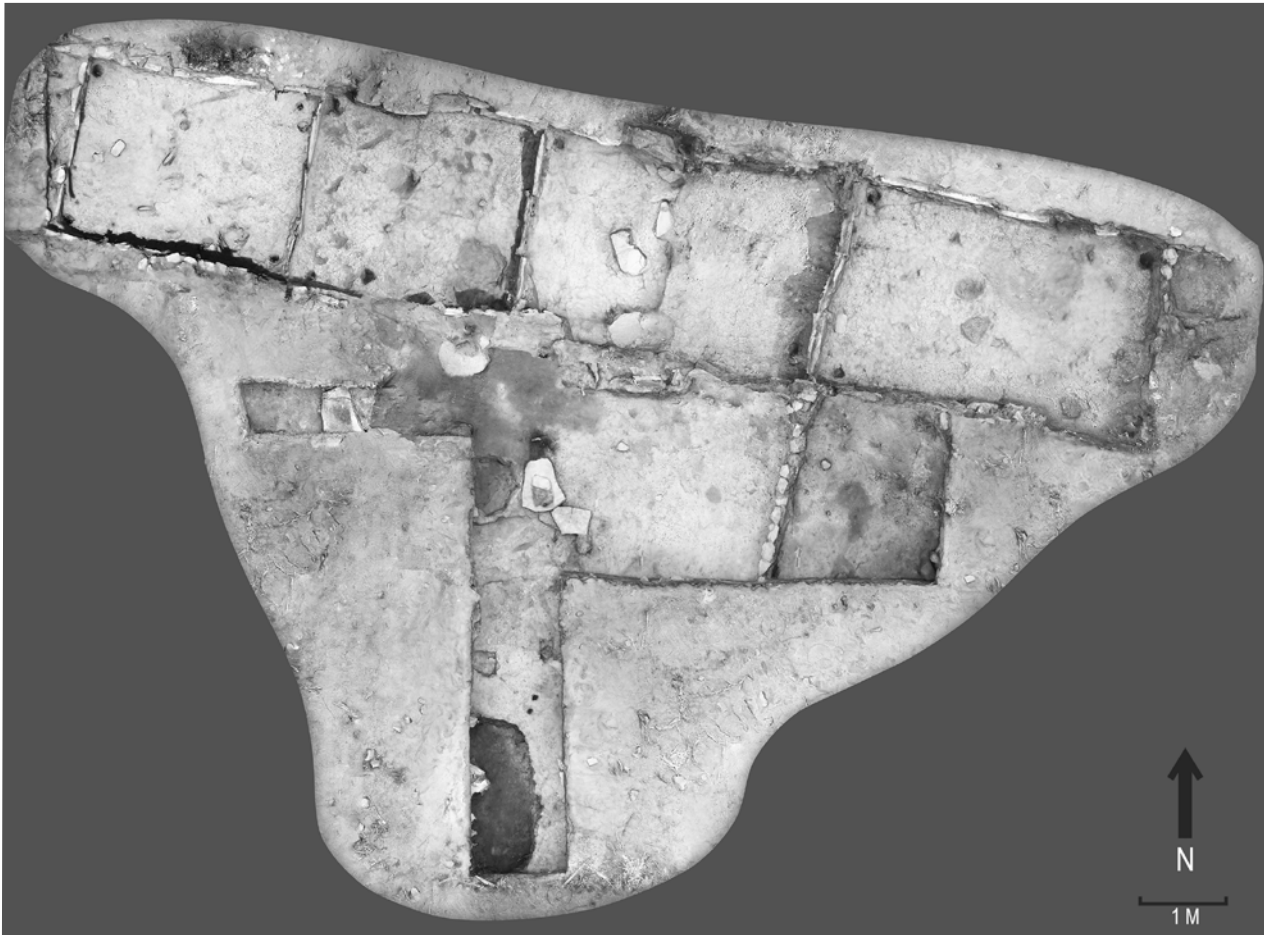
Figure 7. Render of aligned 3D models from Alkali Ridge Site 13. This model uses photographs taken in 2012 of the three rooms at the upper right and photographs taken in 2013 of the room at the upper left and the partially excavated rooms in the lower part of the photographs.

lens with different zoom levels, which is strongly not recommended for photogrammetry. Some photographs also have people and various objects inconsistently moving between shots. Also, there are some areas with too few photographs to construct a completed 3D model. A few photographs were unusable, but we were able to create 3D models of all the desired features. This was done without masking any of the moving objects, which saved time. We combined models of Structure 2 from the 2012 excavation, the antechamber from 2013, Structure 1 as excavated in 2010, a pit in this structure that had to be modelled separately, and the remainder of Structure 1 as excavated in 2016. Of these models, only Structure 1 from 2016 was made from photographs intended for photogrammetry (these photographs were captured via an unmanned aerial vehicle).

The alignment of the models was accomplished using the plan map of the combined structures to align the photographs within Blender. One benefit of aligning the models this way is that we realized that the antechamber had been placed in the incorrect position on the map by almost a meter. This demonstrates an immediate benefit of these 3D models, in that they can eliminate some human error and are usually more accurate than hand-drawn maps. Figure 4 shows an orthographic render taken directly above the structures. The 3D models have several small holes where sufficient overlap was lacking. For aesthetic purposes, these holes can be repaired using 3D modelling software, or, if 2D renders are the concern, image editor software may be used to clean the holes, rough edges, or other problems, as was done in Figure 4. As discussed in the methods section, the accuracy of this model is comparable to a high-resolution laser scan. Photographs from the next site were taken using the same camera and the accuracy appears to be similar except for thin, stone slabs that were

Figure 8. Render of color 3D model of Nancy Patterson kiva. All photographs were taken in the same year.

problematic for photogrammetry using the available photographs.

Alkali Ridge Site 13

Alkali Ridge Site 13 is an Ancestral Pueblo village in southeastern Utah that dates to the late AD 700s. As one of the earliest aggregated villages in the Four Corners area (so-called because it is near where the corners of the states of Utah, Colorado, New Mexico and Arizona meet), it is an important site in the archaeology of the U.S. Southwest. A large portion of the site was excavated in the 1930s (Brew 1946); recent work at the site in 2012 and 2013 included re-excavating several of the rooms that had been excavated 80 years earlier, then expanding those excavations into adjacent unexcavated rooms. The impetus for creating 3D models of the excavated surface rooms at this site are similar to the reasons listed for the Wolf Village case study. Three rooms were excavated and photographed in 2012. One additional complete room and portions of two others were excavated in 2013, but the 2013 excavations were not immediately adjacent and closing photographs did

not overlap between these areas. We created four 3D models from excavations over these two years and combined them into one model. Compared to Wolf Village, there were fewer usable photographs, and there were a greater number of objects and people in the photographs, but the greatest difficulty was the presence of relatively thin stone slabs lining the walls of the rooms. These difficulties led to several distortions in addition to the holes in the model; however, the general physical shape of the rooms turned out well and should be comparable in accuracy to the 3D models created for Wolf Village. These models were aligned by using comparable features in each model, which were later compared with an aligned plan map to verify accuracy. We found the accuracy sufficient for our purposes and, aligned together, these models allow us to render the equivalent of an aerial orthophoto (see Figure 7).

We also attempted reconstruction of some of the same rooms from photographs taken during the original excavations in the 1930s. While we were able to generate some 3D data, overall, we were unable to generate anything useful, even after attempting to add numerous manual tie markers in
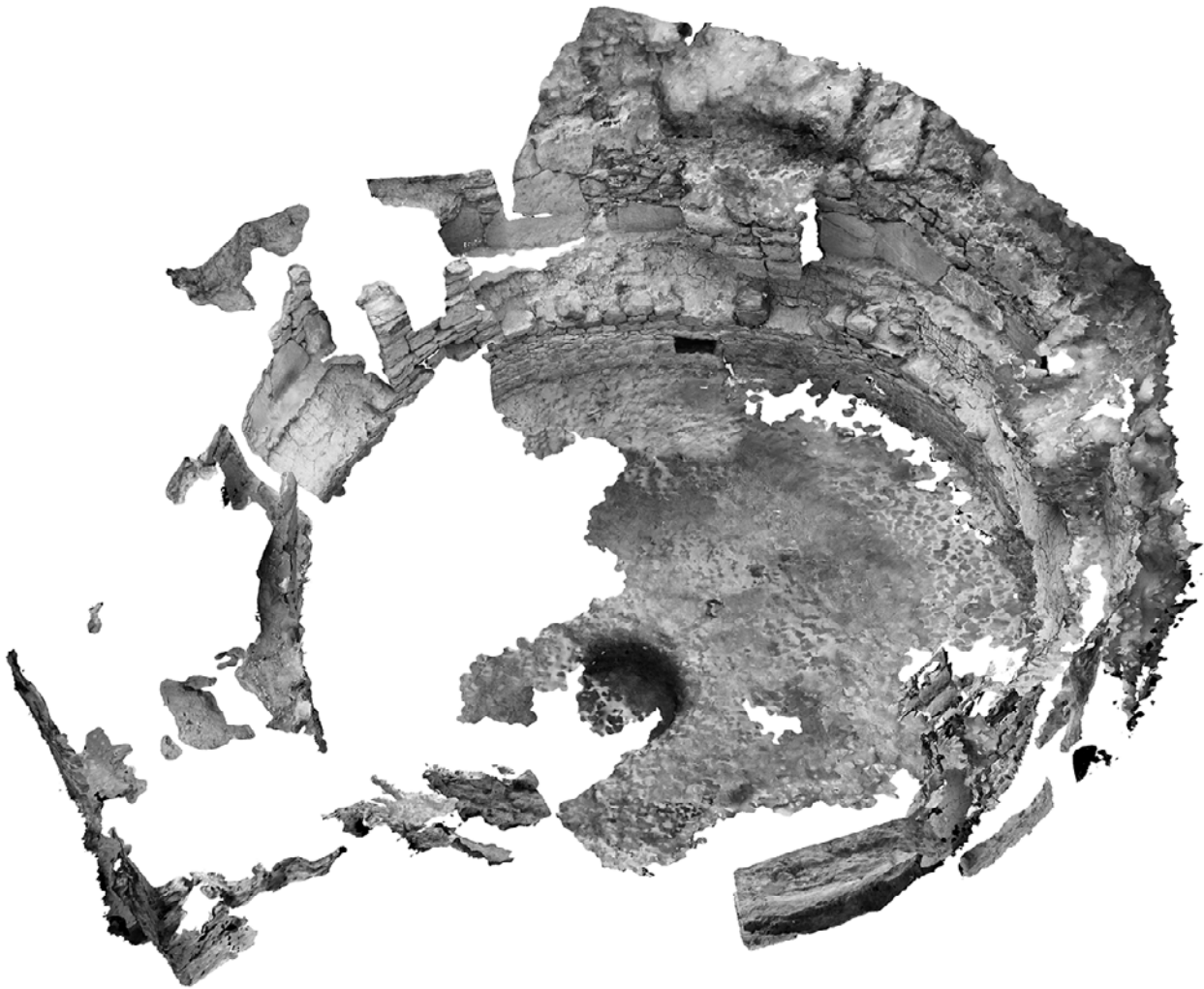
Figure 9. Render of black and white 3D model of Nancy Patterson kiva. All photographs were taken in the same year.

an attempt to force the software to recognize associations between photographs. While the alignment of some photographs was encouraging, we found that we lacked sufficient coverage to create a viable 3D model.

Nancy Patterson Village

Our last study was a reconstruction of a kiva from the Nancy Patterson Village site, another Ancestral Pueblo site in southeastern Utah (Thompson et al. 1986, 1988). The site was used for hundreds of years, beginning in the AD 600s, but it was a large village at two different time periods: close to 900 and again in the 1200s. The kiva we attempt to model dates to the 1200s occupation. It was trenched in 1984, then most of it excavated in 1985. Unfortunately, the depth of the structure, extraordinarily hard fill, the complexity of digging through and documenting the burned

roof fall, and limited manpower meant that the field season ended before the floor could be completely cleared. The kiva was partially backfilled but was still damaged by water pooling in the structure over the winter. By the start of the 1986 field season, some masonry had slumped off the wall. The excavation was finished in 1986, but we were left with photographs from 1985 that showed most of the kiva with masonry intact, but the floor not completely exposed, and photographs from 1986 that showed the floor but with damaged masonry. We therefore hoped to be able to combine photographs from the two seasons to create a model that combined photographs from the two field seasons to show the structure as it would have appeared if fully excavated and undamaged.

Photographs on the project were all taken with paired 35mm SLR cameras, one with color film, the other with black-and-white, with the goal of produc-

ing approximately duplicated photographs with each film type. Slides were digitized using a high-resolution scanner. No metadata exists for these photographs. Our goal was to use both the black and white and color photos; thus, we converted the color photographs into grayscale. Each camera was aligned separately as best as possible and then the camera calibration was saved. When both cameras were calibrated the photographs were added together and the separate calibrations were assigned to each photo. Unfortunately, we were unable to align any cameras without significant distortion; however, we were able to create 3D models out of the photographs from the separate cameras using photographs from 1986. The color model, as shown in Figure 8, has many holes, but the modelled geometry appears accurate. The black and white 3D model (see Figure 9) provided more coverage, but the geometry is clearly more distorted, particularly the floor of the structure. It also took many more attempts to align the cameras than for the color model. The biggest problem with this structure is that most photographs were taken close up of separate features, and the overview photographs did not capture all sides of most parts of the kiva. We found that we lacked sufficient photographs to accomplish our purpose of merging the models to create an intact model prior to the damage between excavation seasons.

Discussion and Conclusion

The goal of this study was to experiment with photogrammetry using photographs not explicitly meant for 3D modelling. These photographs came from both recent excavations and photographs held in archives for decades. These photographs cannot be considered optimal for photogrammetry based on technical reasons, such as a variable zoom lens, missing information, such as camera metadata, and particularly for the lack of sufficient overlap between photographs. Our purpose for these models was primarily visual, and, in some cases, we were able to obtain high quality overviews of architectural features, including the equivalent of aerial orthophotos. We found the ability to combine models made during different excavations seasons to be particularly useful. Using photogrammetry, we were able to take standard excavation photos and create models show-

ing features in contexts that did not exist during excavation. Other than lack of adequate overlap, which is difficult to rectify (although see Wallace 2017), camera alignment is the principal difficulty. This step, typically automatic, often requires time-consuming manual adjustments and experimentation with settings. Additionally, our comparison between a 3D model created from nonoptimal photographs and a precise laser scan demonstrates that these 3D models can attain accuracy comparable to a high-accuracy laser scanner.

Acknowledgements

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