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Structure from Motion: Twenty-First Century Field Recording with 3D Technology

Matthew Howland manipulating the balloon during a typical bi-daily recording session at Khirbat Nuqayb al-Asaymir.

Matthew D. Howland, Falko Kuester, and Thomas E. Levy

Archaeology as a discipline has always faced an ironic challenge. In order to improve our understanding of the past, it is nearly always necessary to destroy the source of knowledge as material remains left by past people are removed from their context. Archaeologists have long understood the responsibility this paradox confers on them—the imperative to record in great detail that which they demolish through excavation so that others may reinterpret their results (Wheeler 1954). The duty of documentation for the purpose of preserving dovetails with efforts toward recording for the excavators' own interpretation of the evidence uncovered. Traditionally, this process has occurred in notebooks through detailed descriptions of archaeological contexts, along with photographic and hand-drawn depictions of excavation. These methods, while tried-and-true, suffer from collection biases, omissions, and an inability to record in three dimensions. In a perfect world, archaeologists would be able to record the conditions of excavation in such a way that future researchers would be able to experience the site exactly as it appeared as it was excavated. Exclusively two-dimensional descriptions of the three-dimensional world falls short of this ideal, especially in a field of study that relies so fundamentally on interpretation of spatial relationships, both horizontal and vertical. Omissions in recording caused by collection biases are equally unacceptable. As archaeologists today bemoan the poor recording standards of 100 years ago, we can assume that the archaeologists of the future will find fault with our work today in a similar way. Traditional methods no longer appropriately fulfill the archaeologist's responsibility for extensive documentation with all practical and available means. How then can we remedy this issue and strive for a more comprehensive documentation program in which datasets more closely reflect conditions in the field during excavation? 3D recording may provide an answer to this critical question, while also providing a mechanism to upgrade traditional techniques.

Thanks to the ever-increasing pace of technological development, several methods of 3D recording are now possible. For the archaeologist, two are particularly prominent and relevant: laser scanning and Structure from Motion. Laser scanning has been widely applied to archaeology in recent years, both in terrestrial and aerial LiDAR forms (Doneus and Briese 2006; Lerma et al. 2010; Margottini 2009). This technology allows for the creation of highly accurate and precise point clouds, which can serve as a three-dimensional record of an archaeological site or as the basis for measurements of features at the site. However, laser scanning is not always a practical solution to the problem of 3D recording for field archaeologists. Terrestrial laser scanners cost on the

Figure 1. The LAAP system in action. Photograph by T. E. Levy.

order of several thousand dollars, with aerial LiDAR scanning costing even more as it requires the expense of planning custom flights across sites in order to scan them. The process of terrestrial laser scanning also requires that users capture multiple scans of the same target in order to avoid occlusions in the data. This is a time-consuming process that can eat into excavation time, the most valuable commodity on an excavation. Laser scanning also requires a good deal of post-processing in order to derive good, spatially-referenced data for the project GIS. Field archaeology requires a cheaper, quicker, and more efficient recording process with results that may prove immediately useful. To meet these criteria while still capturing 3D data and retaining accuracy and precision, archaeologists have increasingly turned to Structure from Motion (SfM) recording—a technique that allows for the creation of 3D models from photographs (Olson et al. 2013; Lambers et al. 2007; Ortiz Sanz et al. 2010). SfM is efficient in the field, accurate and precise in the lab, and provides an ideal solution to the problem of finding a practical method of 3D field recording.

The UC San Diego Edom Lowlands Regional Archaeology Project (ELRAP), focuses on the role of technological change on social evolution viewed through the lens of ancient mining and metallurgy, and has continuously striven to update its field recording system since 1998, when it embraced an all-digital archaeological recording system in 1999 (Levy et al. 2010: 235; Levy et al. 2001). ELRAP's focus on effective digital field recording since the turn of the millennium has pre-adapted the project to allow for the adoption of new digital techniques of ever-increasing sophistication, while retaining the simplicity and practicality fundamental to archaeological fieldwork. ELRAP's adoption of SfM in 2012 provides just such a case. The project had previously developed a custom balloon-based, low-altitude aerial photography (LAAP) system (fig. 1) for the purpose of acquiring vertical imagery to be subsequently georeferenced for the purpose of digitization of archaeological features. This system consisted of a large balloon (ca. 3.6 m x 3.0 m, volume: ca. 21.0 m^3, and lift: ca. 13.6 kg) tethered to and manipulated by a ground-based operator, and a custom triangular frame (fig. 2) capable of holding two high-resolution (15.1 megapixel) Canon EOS 50D Digital Single-Lens Reflex (DSLR) cameras equipped with 18–135 mm lenses. This system, excellent for acquiring quality single images, was already well-suited to acquire the tens or hundreds of high-resolution images appropriate for SfM processing. With the prospects of creating an enormous photographic dataset, the challenge of processing raw camera files into 3D models and GIS data was significant. However, ELRAP's endeavors prior to 2012 allowed for a straightforward solution to this problem. Since the project had already developed a digital lab to work with GIS, pottery scanning, and some laser scanning data, the hardware to implement an SfM workflow was already in place. By simply installing the commercial software package Agisoft Photoscan on one of the desktop computers in the field lab, ELRAP was able to develop a fully-functioning 3D documentation lab with only the additional cost of the software itself to account for.

A serious commitment to archaeological field recording provides a double payout, beyond simply meeting the responsibility of modern excavation to record what is destroyed. Documenta-

Figure 2. The custom balloon platform and cameras being assembled at Khirbat Faynan, Jordan. Photograph by T. E. Levy.

tion of excavation allows for one to preserve the context of excavation for future researchers or current collaborators to experience the conditions of the site as it occurred during excavation. Recording of features at the site is the critical focus of archaeological investigation, and aids researchers in interpreting the past from the evidence remaining. Archaeology is a field that fundamentally deals with spatial relationships, and the modern standard of doing so is within a GIS framework. Thus, the first priority of the ELRAP field recording campaign was to generate high-quality spatially-referenced data suitable for GIS analysis and site mapping. Fortunately, SfM-based recording is well-suited to producing such data. Developing 3D models of excavation units allows one to produce orthorectified[1] vertical imagery of these targets, free of the lens and elevation distortions inherent to unprocessed vertical imagery. Furthermore, Agisoft Photoscan allows the user to georeference models based on control points, facilitating the export of georeferenced orthophotographs. These images provide an excellent basis for direct digitization of features in GIS, a process that eliminates much of the human error produced and propagated by traditional techniques of manual drafting. Given these advantages, ELRAP made the decision to transition from the existing program of feature digitization based on one georeferenced image to an SfM-based recording system—allowing for improved recording with photorealistic 3D documentation as an added benefit.

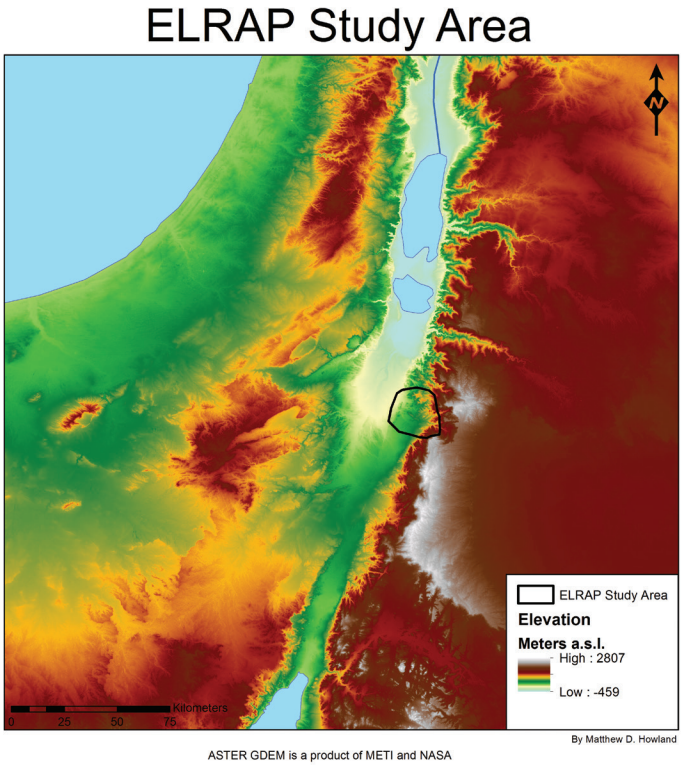

Figure 3. The UC San Diego - Department of Antiquities of Jordan ELRAP study area. Map by M. D. Howland.

In order to appropriately record excavation units with SfM modeling, ELRAP team members developed a custom strategy of photographic data capture, applying it to excavation at several sites in the ELRAP study area (fig. 3). The sites recorded in this manner included multi-period Khirbat Faynan, Neolithic period Wadi Fidan 61, and Middle Islamic IIa period Khirbat Nuqayb al-Asaymir. The team recorded each excavation unit

at these sites with the LAAP system two times per day—before the start of excavation in the morning and during a late-morning lunch break at the site—without interruption to normal excavation. ELRAP team members manipulated the balloon in transects across excavation areas at a height of ca. 10–25 m with the goal of attaining approximately 60 photographs per unit with 50% overlap between adjacent images. This type of overlap is ideal for SfM-oriented photography, which requires that there be substantial crossover between photographs in order for the program to identify identical points across different images. Each excavation unit required approximately 15–25 minutes of time in the field to capture the imagery suitable for the creation of a 3D model of the unit. Recording of the excavation was performed prior to excavation in the morning and during a late morning break, which—in combination with the efficient photography process—meant that no break from excavation was needed for the recording process. Each unit was also outfitted with 6–8 semi-permanent markers, visible in photographs and on the models so that these would be identifiable later for the purpose of georeferencing the model. Transects were designed in order to include these markers in the photographic dataset, allowing for a collection strategy well-suited to the acquisition of georeferenced 3D data through SfM.

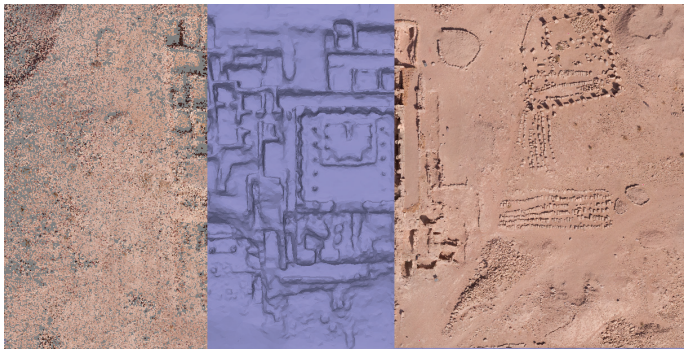

Figure 4 (above). 3D model of the Temple of the Winged Lions at Petra, with the three main phases of SfM processing. From right to left: point cloud, mesh, texture.
Figure 5 (below). Digitization of features underway on orthophoto background. Images by M. D. Howland.

With the photographic data collected and sorted appropriately into the ELRAP project database after each day of data collection, the next order of business was to process the data to create 3D models and subsequently orthophotos of the excavation units recorded on that day. Agisoft Photoscan, currently ELRAP's preferred software, provides a user-friendly, fully-integrated SfM workflow, bringing data from digital photographs to photorealistic 3D models and GIS data in only a few clicks (Verhoeven 2011). Photoscan divides the SfM process into four main stages (fig. 4). The first step in processing photos consists of generating a sparse point cloud—essentially a collection of the points the program is able to identify in the scene across multiple images. With these points and EXIF (exchangeable image file format) data from the camera, Photoscan is able to triangulate the locations from which the photographs were taken with no manual input. This sparse point cloud can be fleshed out into a denser version with more points in a subsequent, optional step. The second main stage of processing consists of the program building a 3D mesh model based on the point cloud generated previously. The final stage of model building gives photorealistic texture to the model, as the images used to build the 3D scene are layered onto the model itself. Each of these stages allows for specification of the degree of detail in the model, enabling the user to prioritize processing speed or quality as needed (naturally, the ELRAP team applied the maximum practical specifications when generating data for research purposes). To provide scale to the model and georeference it, it is a relatively straightforward process to manually identify control points on images or on the model itself and enter their location in a preferred coordinate system. With the model located in coordinate space, Photoscan allows for the export of georeferenced products such as orthophotos and digital elevation models (DEMs).

The generation of orthophotos was, as described above, the highest priority for the recording of excavation units. These images, produced daily, were brought into the ELRAP GIS lab and served as the basis for digitization of archaeological features in ArcGIS by undergraduate students under the supervision of project staff (fig. 5). The additional possibility of developing DEMs also allowed ELRAP team members to generate accurate and precise sitewide elevation data with only a slight modification to the workflow applied to excavation units. The multiscalar nature of SfM recording in archaeology has been noted (Olson et al. 2013). Indeed, the versatility of the technology is one of the benefits that most recommends the technology. By flying the balloon at a height of ca. 80–150 m in more widely-spaced transects, we were able to collect overlapping imagery across the entirety of sites as large as 8 ha in as little as 1.5 hours. The ELRAP team recorded the sites of Khirbat Nuqayb al-Asaymir, Wadi Fidan 61, Iron Age/Roman Khirbat al-Ghuweiba, and Petra in this way (Jones et al. 2012; Ben-Yosef et al. 2013, Levy et al. 2012). The images acquired at these sites were sufficient to produce high-

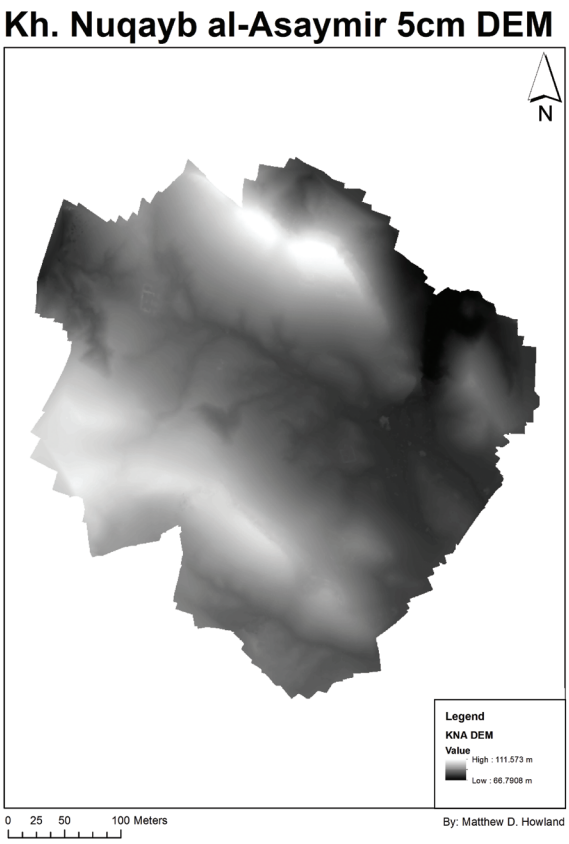

Figure 6. Digital Elevation Model of Khirbat Nuqayb al-Asaymir. Image by M. D. Howland.

quality 3D models of each. Furthermore, the GIS data generated through this method is of substantially higher resolution than comparable forms of satellite-derived data. The sitewide modeling described here allowed ELRAP to acquire 2 cm resolution orthophotos and 5 cm resolution DEMs—orders of magnitude better than the ca 0.5 m resolution imagery and 15 m elevation data available from satellites (fig. 6). These high quality datasets serve as excellent basemaps, or as a basis for more detailed forms of spatial analysis. In particular, the ELRAP team has used the 3D data acquired through this structure from motion workflow to undertake detailed simulations of the effects of erosion on the development of archaeological sites; an analysis not practical without SfM-based recording.

Recognizing the responsibility of detailed and accurate field recording, the ELRAP team has undertaken a never-ending quest to find the most effective system of field recording. The most recent update has had a twofold benefit: improved accuracy of recording, while also collecting 3D data that accurately preserves the conditions of excavation. Structure from Motion appears not only to be one of the most accurate and precise techniques for georeferenced recording of archaeological features, but is also the most efficient form of 3D documentation in the field, while still remaining a practical and cheap method. By bringing excavation into the twenty-first century, archaeologists can improve the accuracy of their own work while meeting the responsibility of recording excavation for future researchers, all with a minimum of time and money. What's not to like?

Note

1. Orthophotos are aerial photographs that are geometrically corrected or "orthorectified" so that the scale is uniform, effectively becoming a map that lacks distortion. Orthophotos can be used to measure true distances because they are accurate representations of the surface of the earth.

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