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Tunnel Vision

Documenting Excavations in Three Dimensions with Lidar Technology

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In 1876, Charles Warren described his method of tunneling excavations in Jerusalem as follows: "We mined in this case down to the rock, and then run along its surface until we reached the great wall, and there we commenced our work, examining the masonry" (Warren 1876:149). Warren headed underground because he had angered a local sheik in his search for Herod's Temple, which lay beneath the Haram al-Sharif. While the ethics of this somewhat secretive approach have been rightfully questioned, the tunneling methodology stands as a meaningful contribution to archaeological

ABSTRACT

Archaeological tunneling is a standard excavation strategy in Mesoamerica. The ancient Maya built new structures atop older ones that were no longer deemed usable, whether for logistical or ideological reasons. This means that as archaeologists excavate horizontal tunnels into ancient Maya structures, they are essentially moving back in time. As earlier constructions are encountered, these tunnels may deviate in many directions in order to document architectural remains. The resultant excavations often become intricate labyrinths, extending dozens of meters. Traditional forms of archaeological documentation, such as photographs, plan views, and profile drawings, are limited in their ability to convey the complexity of tunnel excavations. Terrestrial Lidar (light detection and ranging) instruments are able to generate precise 3D models of tunnel excavations. This article presents the results of a model created with a Faro™ Focus 3D 120 Scanner of tunneling excavations at the site of El Zotz, Guatemala. The lidar data document the excavations inside a large mortuary pyramid, including intricately decorated architecture from an Early Classic (A.D. 300–600) platform buried within the present form of the structure. Increased collaboration between archaeologists and scholars with technical expertise maximizes the effectiveness of 3D models, as does presenting digital results in tandem with traditional forms of documentation.

La excavación de túneles es una metodología común en Mesoamérica. Los antiguos mayas construyeron edificios nuevos encima de los que ya no eran usables, quizás por razones logísticas o ideológicas. Este quiere decir que cuando los arqueólogos excavan túneles horizontales en las estructuras mayas, están pasando atrás en tiempo con su profundidad. Cuando se encuentra subestructuras, estos túneles pueden desviar en direcciones varias en el proceso de registrar la arquitectura enterrada, la cual normalmente es mejor conservada que los edificios más tardes de la superficie. Las excavaciones muchas veces se convierten en laberintos, extendiendo para docenas de metros. La documentación arqueológica tradicional, en la forma de fotografías, plantas, y perfiles tienen límites en lo que se pueden mostrar de la complejidad de los túneles. Los instrumentos de Lidar (detección de luz y rango) terrestres se pueden generar modelos 3D precisos de las excavaciones en túneles, documentando los rasgos arqueológicos con detalle increíble. Este articulo presenta los resultados de un modelo creado con un Faro™ Focus 3D 120 Scanner de las excavaciones en túneles en el sitio arqueológico El Zotz, Guatemala. Los datos de Lidar adquirido registran las excavaciones adentro de una gran pirámide mortuoria, incluyendo arquitectura elaborada con estuco modelado del Clásico Temprano (300–600 d.C.) de una plataforma enterrada. Los datos coleccionados se puede usar para crear caminatas virtuales de las excavaciones y conservan toda la información de los túneles aún están rellenados. La colaboración entre arqueólogos y especialistas en tecnologías digitales aumenta la eficaz de los modelos en 3D, y también la presentación de estos modelos juntos con la documentación tradicional.

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investigation, especially in its unintended goal of preserving cultural overburden in the investigation of earlier occupations.

Tunneling quickly fell out of favor in Old World archaeology as trenching became the preferred method for investigating large settlements. In Mesoamerica, however, tunneling was adopted as an excavation method early on (see below) and is now standard practice in the excavation of many large structures, especially pyramids and platforms. These tunnel systems can become labyrinthine, as they extend in different directions, horizontally and vertically, tracing the vestiges of earlier architecture. Documenting such excavations can be challenging, and the resulting plan and profile drawings often distill the true complexity of the operation. This article examines the use of terrestrial lidar technology for the three-dimensional (3D) documentation of tunneling excavations. This highly accurate method of recording spatial data allows for the generation of precise models that allow investigators to see a realistic rendering of archaeological tunnels. The collected data set can be used to view the excavations themselves, as well as archaeological features detected within the tunnels. Documentation carried out at the lowland Maya archaeological site of El Zotz, Guatemala (Figure 1), is offered here as an example of the utility of this method.

ARCHAEOLOGICAL TUNNELING IN THE MAYA LOWLANDS

The ancient Maya built up the mass of their cities by incorporating structures that had fallen out of use into later constructions at the site. These earlier buildings may have deteriorated to a point beyond repair, or they may have lost their ideological significance. Often, the accession of a new ruler (the *k'uhul ajaw*) to the throne would inspire a flurry of new building activity, which would entomb structures from the previous reign underground as the new king made his own imprint on the urban landscape. In cases of elaborately decorated buildings, the Maya would sometimes make deliberate efforts to preserve the earlier buildings during their interment. The problem arises of how to access these earlier structures without destroying the later versions on the surface.

The twentieth-century excavations of Tikal Temple 33 (Coe 1990) and Uaxactun Structures A-V and E-VII (Ricketson and Ricketson 1937; Smith 1950) stripped the final phase buildings, and the overlying construction is now physically lost, despite thorough documentation. Archaeologists from the Carnegie Institution of Washington experimented with tunneling in some of their early excavations at Chichen Itza in Mexico (Ruppert 1952) and Copan in Honduras (Stromsvik 1952), revealing spectacular substructures while leaving surface ruins intact. Apparently, Gustavo Espinoza also experimented with tunneling in Guatemala at the site of Kaminaljuyu in 1958 and 1962, though those excavations were never published (Houston et al. 2003).

It was not until the 1980s, through the efforts of Juan Pedro Laporte and Juan Antonio Valdés at Tikal and Uaxactun (Laporte and Fialko 1985; Laporte and Valdés 1993), and William Fash, Robert Sharer, and Ricardo Agurcia at Copan (Agurcia and Fash 2005; Fash and Agurcia 2005; Fash and Sharer 1991; Sharer et al. 2005), that archaeological tunneling became a mainstream excavation method in the Maya lowlands. Spectacular discoveries deep within buildings at these sites led to the adoption of tunneling on many subsequent projects. Notable discoveries, such as the San Bartolo (Saturno et al. 2005) and Calakmul murals (Carrasco et al. 2009), and the more recent Temple of the Night Sun at El Zotz (Houston et al. 2015), validate these methods. In the case of the examples from San Bartolo and El Zotz, archaeologists took advantage of existing "tunnels" dug by looters to try to maximize the knowledge that could be gained from their destructive activities.

REPRESENTATIONS OF TUNNEL EXCAVATIONS IN ARCHAEOLOGICAL PUBLICATIONS

Archaeologists traditionally convey the results of excavations through the use of photography, plan views, and profile drawings. No matter the setting, the publication of archaeological data generally involves transforming a three-dimensional context into a two-dimensional representation. Photographic recording methods on archaeological projects in the Maya lowlands are inconsistent, but the University of Pennsylvania's Tikal Project (1956–1970) established many of the drafting conventions accepted today for plan and profile drawings (Coe and Haviland 1982). Despite this consistency, the flattening of tunnels into two-dimensional drawings still obscures the intricacies of the excavations themselves.

Photography

There are diverse approaches to photographing archaeological tunnels in Maya archaeology. Each tunnel excavation is unique in terms of its vertical and horizontal dimensions, physical layout, and cultural features encountered. Furthermore, the quality of photographic equipment available is widely variable on projects, not to mention the knowledge and skill of the person taking the photograph. The tight spaces and extreme humidity common in tunnel excavations can make it difficult to capture features discovered through digging. In documenting the San Bartolo murals, William Saturno (2009) used a flatbed scanner to directly record the paintings and then stitched the scans together as a mosaic in Adobe Photoshop™. This allowed for precise artistic renderings of the murals by Heather Hurst. Saturno's method, while great for the flat, smooth mural surfaces, is not useful for documenting exterior architectural decorations in the form of masks and friezes, which have relief and do not lend themselves to flatbed scanning. In the excavation of the Temple of the Night Sun at El Zotz (Houston et al. 2015), the photographer used a fisheye lens (Figure 2a) and oblique views (Figure 2b) to document the various stucco masks found on a frieze within tunnels less than 1 m wide. This creates a great deal of distortion and does not give the viewer a good sense of the proportions of the feature being photographed. Archaeologists from the Center for Advanced Spatial Technologies (CAST) at the University of Arkansas used near range photogrammetry to document architectural masks at El Zotz (Fisher et al. 2012). The resultant images are remarkable (Houston et al. 2015), but required months of post-processing and additional trips to the field to

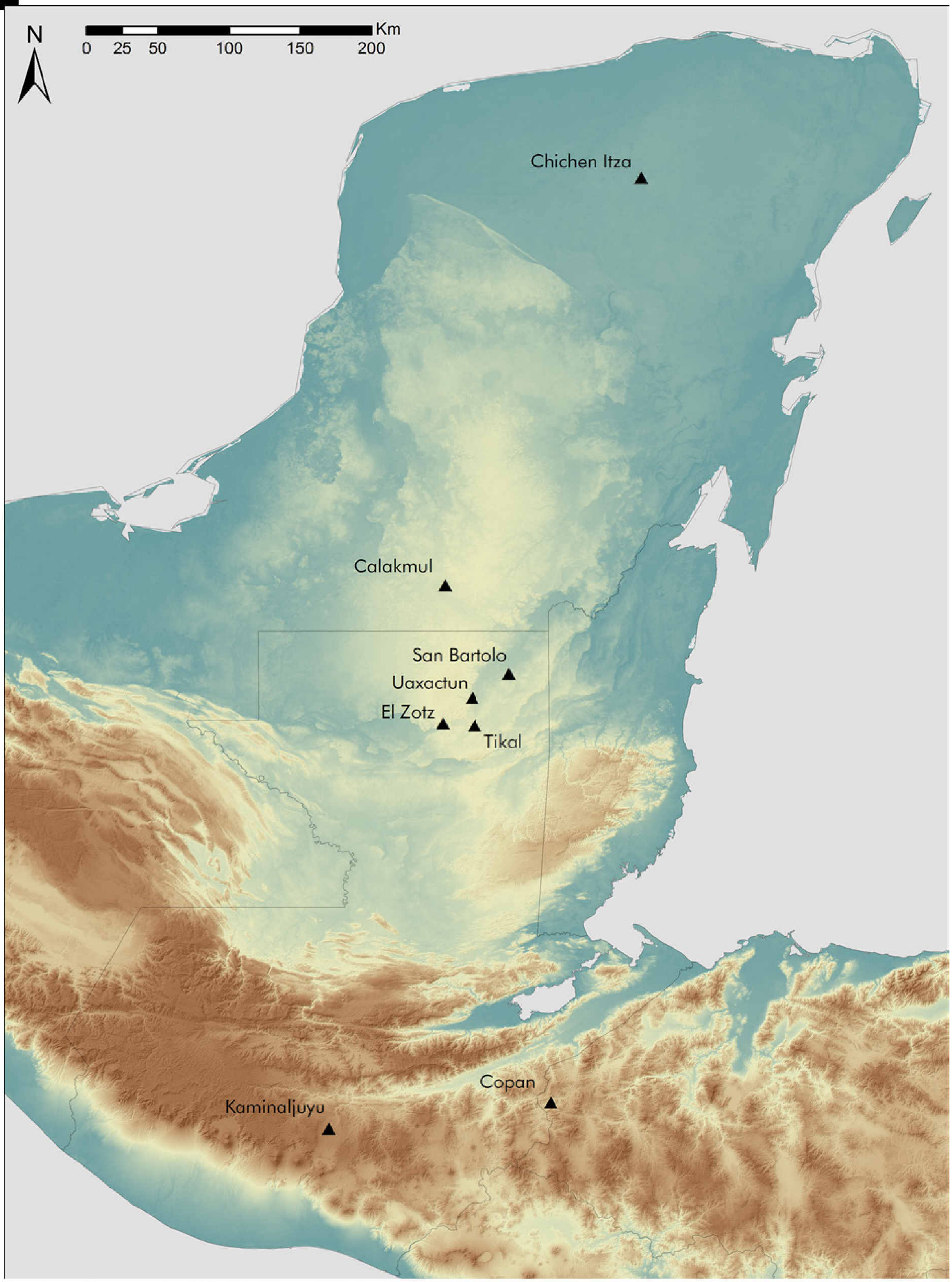

FIGURE 1. Map of the Maya area with sites mentioned in the text (map by T. Garrison).

a. b.

FIGURE 2. (a) Photo of one of the northeast corner mask of the Temple of the Night Sun taken with a fisheye lens; (b) oblique photo of the mask on the north side of the Temple of the Night Sun (photos by A. Godoy courtesy of Proyecto Arqueológico El Zotz).

fill in gaps in the original documentation. Lidar documentation, to be discussed below, has the capability to document architectural features rapidly and precisely, even in close quarters.

Plan Drawings

The Tikal Project set the standard conventions in Maya archaeology for plan drawings of excavations at a scale of 1:50, which was necessary given the extensive nature of such operations (Coe and Haviland 1982). In the case of Copan, where there are several kilometers of tunnels beneath the Acropolis, archaeologists have been able to create full-scale site reconstructions of earlier versions of the city, prior to the Late Classic constructions that remain on the surface (Fash 1998:Figure 4). However, plan views of tunnel systems that encompass multiple construction phases beneath a single structure can become quite complex and require precise labeling and explanation to make them intelligible to readers.

Recent work at the site of El Zotz highlights some of these issues. Looters burrowed into El Zotz Structure M7-1 ("Pyramid of the Wooden Lintel"), most likely in the 1970s. In 2012, Garrison began clearing out debris from the 28.8 m of horizontal illicit tunnel excavations in preparation for new investigations beneath the pyramid. Since that time, an additional 83 m have been excavated as extensions and branches of the looter's tunnels, revealing two major substructural platforms, an earlier version of the surface pyramid, and a series of auxiliary structures, known as *adosados*, that were added to the front of the pyramidal forms of the building throughout the Classic period. All of this is recorded in a 1:50 plan view that represents the cumulative work of three seasons of excavation between 2012 to 2014 (Figure 3). The numerous elevation changes, narrow spaces, and turns in the tunnel system made it impossible to document the excavations with a total station. The plan was hand drawn using baselines and tape measures and then digitally drafted in Adobe Illustrator™. The building designations are standard for architectural documentation in the central Maya lowlands (Houston et al. 2015:32–33).

The Str. M7-1 plan, while technically correct, is still confusing, even to a trained eye. Elevation changes are marked by datums throughout the plan that reference the base elevation at the far western tunnel entrance. Architectural reconstruction drawings of the various building phases are limited so as not to further clutter and confound the image. For example, in Figure 3 the central stairs of Str. M7-1-2nd are extended as dashed lines, connecting with the sides of the pyramid. Also, the upper platform of Str. M7-1-Sub-2 is reconstructed based on the excavated portions along the building's central axis. In places where higher tunnels overlap with the main lower branch, the upper excavations are dimmed to contrast with the darker features beneath. This is particularly noticeable in the case of the small platform on top of Str. M7-1-Sub-2, which sits atop the western portion of Burial 16. The plan is also unable to capture every building phase. For example, Str. M7-1-Sub-1-1st is a modification of an

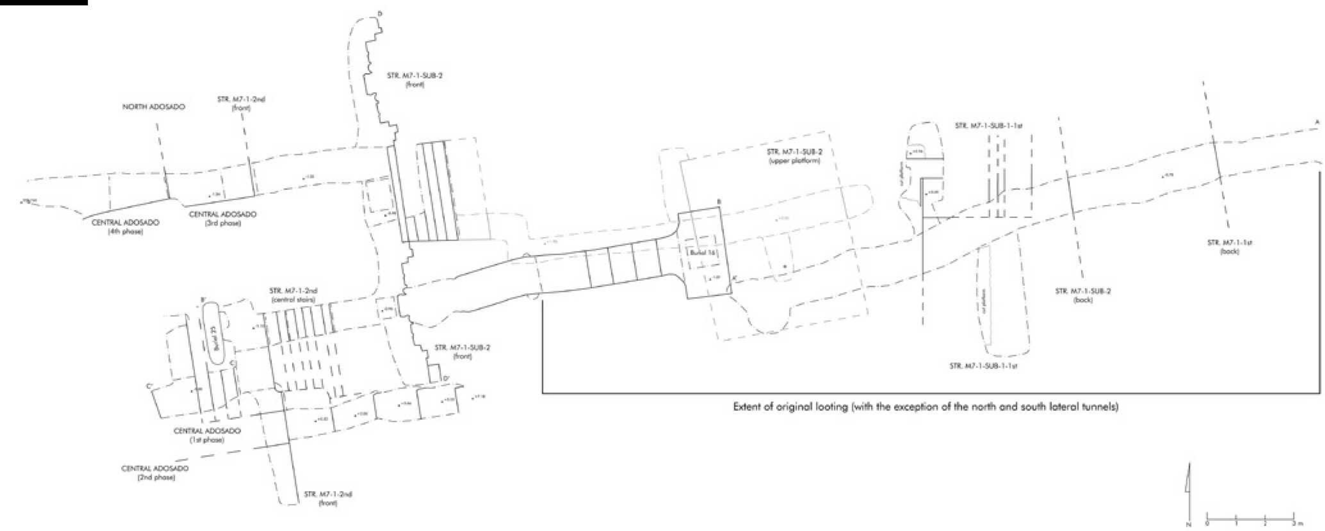

FIGURE 3. Plan of the Str. M7-1 tunnel excavations (drawing by T. Garrison).

earlier version of this platform (Str. M7-1-Sub-1-2nd), and there are no features that can clearly be distinguished from the earlier form in the plan. From a positive standpoint, the plan is very good at showing the change in building orientations between phases. This is clearly seen on the right hand side of the figure when looking at Str. M7-1-Sub-1-1st in relation to the back of Str. M7-1-Sub-2.

Profile Drawings

Archaeologists try to convey the verticality of excavations, architectural composition, and construction sequences through profile drawings. In the Maya lowlands, conventions were once again established at Tikal, with profiles recorded at a scale of 1:20; the goal was to record features in as realistic a manner as possible (Coe and Haviland 1982). In addition, various line weights and hatching techniques are used to convey different types of materials. When recording tunnel systems in profile, the archaeologist must choose between presenting a dizzying array of different sections in order to convey the features encountered during excavation and compressing a winding profile into a straight line so as to present a complete section. In the case of the documentation of Str. M7-1, both of these solutions were necessary.

Figure 4 is the composite northern section of the main east-west profile of the Str. M7-1 tunnel systems. The eastern part of the tunnel represents the extent of illegal excavations, including the looted tomb designated as Burial 16. The looters continued following a passageway that stepped out of the western side of the tomb chamber. They destroyed a crude staircase, which they did not recognize, before abandoning their efforts about halfway down the passage. Moving to the west from that point, the profile documents excavations conducted by the El Zotz Archaeological Project during the 2012 to 2014 field seasons. As extensive as this single long profile is, it unfortunately does not transect all of the major architectural components of Str. M7-1. The complexity of the central *adosado* additions is hidden because the profile intersects only the earliest version of this feature. The drawing renders the profile of the central architectural mask of Str. M7-1-Sub-2 and its associated vaulted passage and royal tomb, but that is at the expense of lateral staircases. A separate tunnel on top of this substructure revealed a smaller platform above. However, that upper platform was oriented slightly differently from the base (see the plan in Figure 3), and because the upper excavation tunnel was offset from the one below, these features could not be rendered together faithfully. There are positive aspects to the profile as well. Unlike in the plan drawing, Str. M7-1-Sub-1-2nd, which is in fact the earliest construction at this locale, shows up clearly beneath its later version. Also, the realistic rendering of the architectural construction fill allows the eye to easily distinguish between different construction methods.

The front of the excavated portion of Str. M7-1-Sub-2 is depicted in profile in Figure 5. These architectural masks depict the Maya

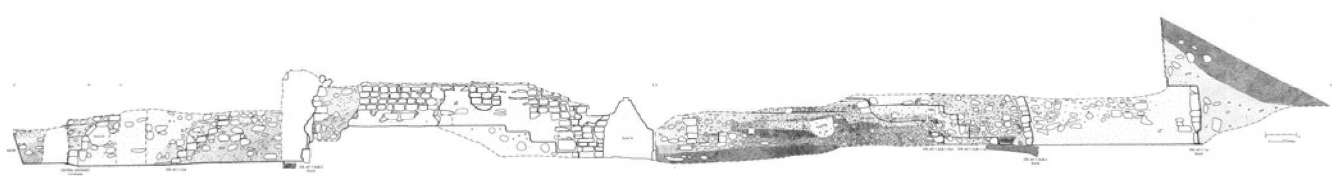

FIGURE 4. Main east-west profile of the Str. M7-1 tunnel system (drawing by T. Garrison and A. de Carteret).

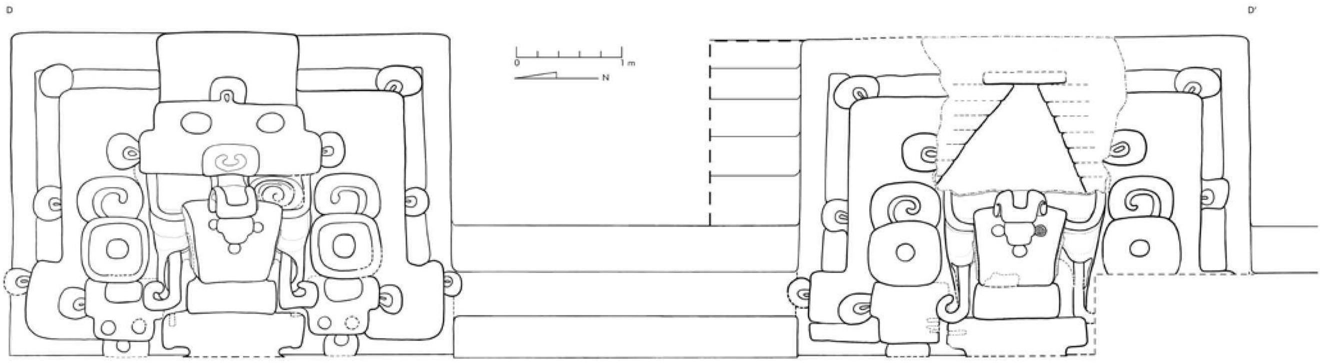

FIGURE 5. Profile drawing of the front of the excavated portion of the Accession Platform (Str. M7-1-Sub-2) (drawing by M. Clarke).

god *Ux Yop Huun*, a deity associated with *amate* (*Ficus sp.*) paper and the ritual of royal accession, during which a paper headband is tied onto the new king's head (Stuart 2012). For this reason, this substructure has been designated as the Accession Platform and may have in fact supported a scaffold throne for the ceremony of a new king's inauguration. Figure 5 is simultaneously an archaeological section and an iconographic line drawing. Line drawings necessarily reduce the complexity of the three-dimensional relief of the rendered feature into established representational norms that will translate for the skilled iconographer (see Hamann [2012] for a critique). Lost in this rendering is the overall architectural context of the iconography. Even the inset staircase is flattened onto the two dimensional plane. The relief of the mask could be illustrated in cross section, but it would display only a single transect of the 4.5-m-wide object. Figure 5, while useful for interpretive purposes, undermines the intricacy of the Accession Platform's iconography.

MATERIALS AND METHODS

Some of the representational issues presented by traditional archaeological documentation of tunnel excavations and their cultural features can be resolved by documenting in three dimensions. Members of the Engineers for Exploration Program at the University of California, San Diego (UCSD; directed by Kastner, Lin, and Schurgers) made two visits to El Zotz in 2014. The team used a Faro™ Focus 3D Scanner 120 to document various looter excavations and archaeological tunnels at the site. After experimenting in various contexts, including in the tunnels around the Temple of the Night Sun, the engineers created a comprehensive 3D model of the tunnels beneath Str. M7-1. This differs from the documentation work done by CAST (Fisher et al. 2012), which focused on the architectural masks, but not on the overall tunnel context.

Faro™ Lidar

The Faro™ Focus 3D 120 Scanner is a light detection and ranging (lidar) sensor. Lidar sensors work by measuring the round-trip time-of-flight of a laser pulse (in this case, a near-IR 905 nm pulse) to deduce the distance of an object from the sensor. The Faro™ lidar uses a mirror to point the laser with .009-degree precision and can collect 122,000 to 976,000 points/second depending on the desired accuracy of each measurement. This accuracy depends on many factors, (i.e., ambient light, distance from the sensor to the object, and reflectivity of the object to the laser pulse, among others) and is typically on the order of 1 mm. The Faro™ has a 305-degree vertical field of view and a 360-degree horizontal field of view, allowing it to obtain an almost complete sphere while scanning. Additionally, the Faro™ can capture color images and integrate the images into the measured point data to give a full-color point cloud.

The Faro™ is easy to work with. It weighs approximately 5 kg, including its 5-hour battery, enabling a user to easily reposition the sensor to scan different areas. It has integrated sensors, such as a level and compass to help rectify the scans in the data processing phase. The major drawback to using the Faro™ in the field is that it is very sensitive to dust, condensation, and shock. The mirror of the Faro™ Focus is exposed to the environment and prone to collecting particulates in the air. The alignment of the mirror is crucial to the accuracy of the measured points and should not be cleaned or touched except by a professional. It is crucial to take care when using the Faro™ for fieldwork, though in the present study, which documented dusty archaeological tunnels, the sensor presented no troubles.

Land-Based Lidar Scanner Applications in Cultural Heritage Research

The data collected by lidar scanners have found their way into many different aspects of cultural heritage research. From site planning, representation, and documentation to structural analysis of statues and buildings, the accurate geometric information of the Faro™ scanner has created new methods of quantitative study. The Faro™ and other sensors like it have driven the development of new software and databases in order to accelerate the understanding and dissemination of archaeology studies. Work by Galeazzi (2016) leveraged a Faro™ scanner to map a Maya cave complex in Belize, which included nine chambers and required 350 individual scans (see also Lindgren and Galeazzi [2013]). This work focused on methodology and the issue of meshing such large amounts of scans, which is addressed here as well. The effects of challenging environmental conditions on both laser scanning and image-based modeling have been studied, and these studies have guided our use of similar technologies. Studies by Blais and Beraldin (2006) investigated accuracy limitations and calibration challenges to obtain highly

FIGURE 6. Lidar scan of the Chahk mask from the north side of the Temple of the Night Sun (compare to Figure 2b). For a manipulable model of this image, see Supplemental Figure 1.

accurate colorized 3D models of an object, but with a focus on infrastructure use in a controlled setting. Another relevant body of work relates to creating 3D models of archaeological cave systems. Gonzales-Aguilera et al. (2009) specifically focused on a multi-sensor approach of laser scanning, total station survey, and photographs. However, the narrow tunnels in our work preclude these methods.

More similar is the work by Grussenmeyer et al. (2012), which aims at modeling and surveying a Paleolithic cave's volume. It relies on targets, as in our study, and combines laser scanning with photogrammetry. Despite the similarities, the high-heat, high-humidity environment in the Guatemala jungle and the narrow tunnel maze present a unique set of challenges. Petrovic et al. (2011) describe a new platform for visualization and analytics driven by the need to understand the massive amounts of digital data collected in Jordan. The software is able to render the large point clouds that were collected in order to manipulate and study the digital data that were collected. This resulted in a shift in the archaeology workflow. Archaeologists were able to direct their digital data collection by examining the previous days, ensuring a complete collection at the conclusion of the field study.

Lidar has been utilized in different studies of structures. Wood et al. (2012) used lidar to determine the geometry of the Palazzo Vecchio in order to analyze the variation of the floor surface, as well as deformation in the walls. This information was collected to determine the causes of the cracks in culturally important frescos in the building so that they could be slowed or prevented. Additionally, Wittich et al. (2012) used lidar to geometrically survey statues in order to estimate the seismic response of the statue. This information provides curators with estimates of the risk associated with the current placement of the statues and can inform engineers how to isolate the structures so that they are robust in relation to seismic activity.

Documenting Archaeological Tunnels at El Zotz

For the present work, we used the Faro™ Focus 3D 120 Scanner to document archaeological tunnels. When operating the scanner, surveyors operated in pairs. One person was responsible for support and documentation, and one operator was responsible for moving and operating the equipment. Notes regarding environment, placement, and abnormal behavior were recorded in a notebook to assist with post-processing. In preparation for scanning, the team would survey the tunnel and plan the tracking object and scan locations on a copy of a 1:50 plan view or hand-drawn map. Individual scans were numbered, while tracking objects were assigned letters. The tracking objects are critical for post-processing, when multiple scans are combined into a cohesive model. A sufficient number of tracking objects guarantees accuracy and minimizes user intervention in post-processing. While combining individual scans into a coherent framework is possible without tracking objects, the use of these

FIGURE 7. Lidar scan of the front of the Accession Platform (Str. M7-1-Sub-2) (compare to Figure 5). For a manipulable model of this image, see Supplemental Figure 2.

objects increase accuracy and reduces post-processing effort. This is especially important when scanning tunnel systems, where scans need to be aligned in a linear fashion and inaccuracies accumulate as more scans are added.

The tracking objects used for this process were primarily FARO™ balls, which can be precisely localized in post-processing but cannot be attached to ceilings, walls, etc. The placement of tracking objects is best described as finding a balance between visibility and stability: tracking objects placed in footpaths were likely to be disturbed while operating the scanner. Tracking objects placed in alcoves were occluded more quickly. Therefore, most of our tracking objects were placed on the ground, at corners and against walls. This created unique challenges, and could have been avoided with more versatile tracking objects.

Scanner placement is critical for producing dense and error-free reconstructions of the excavations. The displacement between scans depends on the detail of the surrounding environment. For example, in a typical excavation tunnel with few archaeological features, the scanner was moved one or more meters between scans. When features of interest were present, the scanner position was moved less; often, the tripod position was not changed, only the height of the scanner. A level surface is not required for operation, but the scanner on the tripod must be within a few degrees of level when the scan is executed. We found that hard surfaces worked best, while small amounts of gravel and dust were also acceptable. In general, when placing the scanner, it is important to stabilize the tripod legs to avoid shifting during operation, such as sinking into loose sand, and to avoid potential damage from falls.

Though the scanner was capable of capturing color images, we did not use this feature. Capturing color doubled the scan time from 3 minutes to 6 minutes per scan, but, more importantly, required uniform illumination across multiple scans. Color is useful in some situations, such as in the Temple of the Night Sun at El Zotz, where color features exist (Houston et al. 2015). In Str. M7-1, there was no paint and low variance in color scheme.

Post-Processing Lidar Data

After the individual scans have been recorded, they must be stitched together to form a cohesive model. For this task, we used the Faro™ SCENE software. In order to combine multiple scans into a cohesive model, each scan needs to be loaded and the tracking objects (targets) identified. We manually identified all visible tracking objects in each scan and matched those between scans, as automatic identification is error prone and does not accelerate post-processing. These correspondences between the scans are used to precisely align the scans together to create a complete model. This is especially important as our scenario involved mainly a linear concatenation of scans.

The quality of the final model depends heavily on the number, placement, and immobility of the tracking objects. Partially occluded targets introduce noise, and perturbed targets cannot be used in post-processing. Scans with insufficient targets cannot be precisely placed in the larger model. In the worst cases, we supplemented the Faro™ balls with other immobile objects such as nails, posts, or light bulbs. However, unlike the Faro™ balls, the characteristics of these objects are not known, so their locations cannot be precisely determined. Therefore, these methods result in poor intra-scan correspondences and an inaccurate final model. In order to obtain high precision in the models, it is important that each scan captures three to four unobstructed balls. The field maps generated by surveyors, noting the scan location and the object position, were crucial during post-processing.

When all correspondences have been marked, the FARO™ software automatically builds a model from all scans, minimizing error in the geometry of the balls. The software evaluates

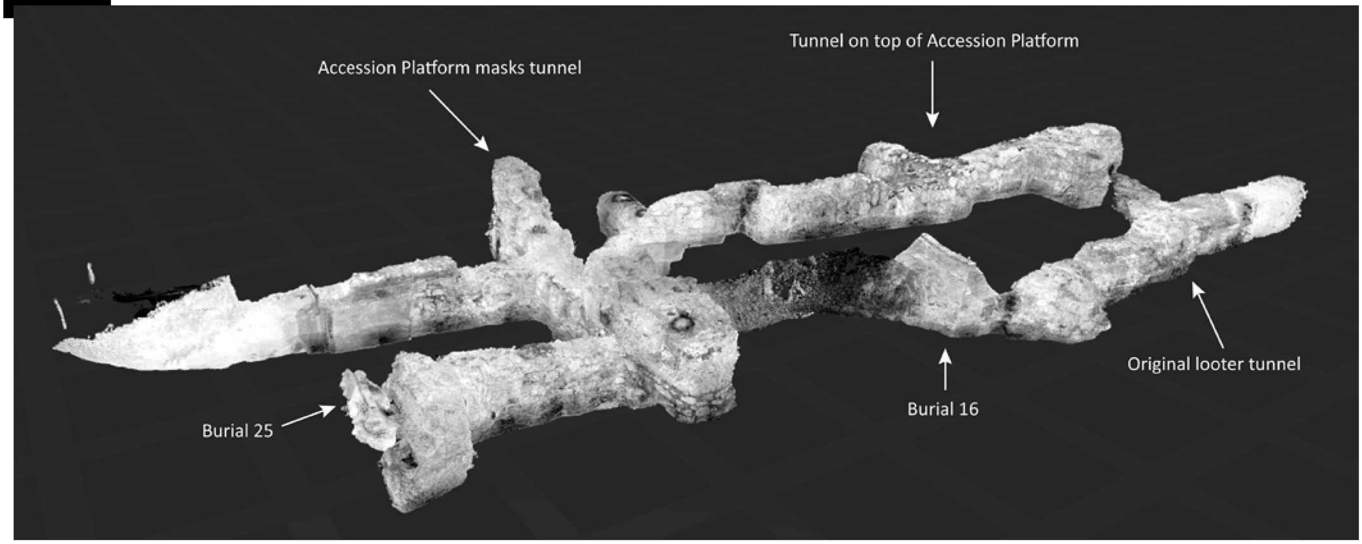

FIGURE 8. Lidar scan of the Str. M7-1 tunnel system with major features labeled. For a manipulable model of this image, see Supplemental Figure 3.

all of the pair-wise correspondences between tracking objects in the final model and ranks the best correspondences. These correspondences are used to evaluate the fit of each individual scan in the overall model. Scans with poor correspondences were misplaced and resulted in a poor model. Manual steps can be taken to improve the correspondences. The final model in SCENE is saved as a point cloud and can be viewed in software developed at UCSD (Petrovic et al. 2011; Petrovich et al. 2014).

The work in Str. M7-1 collected 76 scans, comprised of approximately 2 billion points, and covered about 87 m of tunnels. The point cloud was utilized to generate both still images as well as video fly-throughs (see Supplemental Video 1). Initially, the SCENE software was used to generate this media; however, because of a lack of quality in the final product and poor utilization of computing resources by the software, a different solution was explored. Petrovic et al. (2011) developed software that successfully handles the massive lidar point clouds. The user configures a sequence of waypoints that the camera should travel through, and the program calculates the best path between the waypoints at a given speed. Finally, the software performs a high-quality flythrough and produces high-quality still images at 30 frames per second. These images are combined in standard software, such as FFmpeg, to create a full video. The video uploaded for this article has a lower resolution than what is possible in order to conserve file size.

Faro™ SCENE and UCSD's proprietary software serve different purposes. Faro™ SCENE handles individual lidar scans and stitching well, but suffers when the point clouds become large. Petrovic et al.'s (2011) software outperforms SCENE for high-quality media and demonstrations, but cannot be used to combine scans. However, neither program performs well when removing artifacts in the data, such as when an operator is captured in a scan. Removing such distortions requires further software development.

RESULTS

The 3D documentation of archaeological tunnels yielded a wide array of data. First, archaeological features were documented within their architectural and excavation context. For El Zotz, this means the recording of modeled stucco masks on the Temple of the Night Sun and the Accession Platform. Second, the lidar generated a faithful representation of the network of tunnels beneath Str. M7-1. This allows for the structure of the archaeological context to be understood without flattening it into the two dimensions forced by traditional plan and profile drawings. Finally, the generated scans create a powerful experiential tool that allows for virtual "visits" to the excavations, while protecting the original objects in their context.

Isolating Archaeological Features

One of the priorities of the El Zotz Archaeological Project is the responsible documentation and conservation of the site's beautifully decorated Early Classic period (A.D. 300–600) substructures. It is likely that many of these masks will be reburied at the end of the archaeological project unless there is substantial conservation and investment in development for tourism. As such, a faithful record of the features uncovered is critical, both scientifically and ethically. The lidar scans of the modeled stucco masks from the Temple of the Night Sun and the Accession Platform are unparalleled in their three-dimensional resolution. The recordings were made in black and white, but the model could be used, in theory, as a frame to drape color images, or the tunnels could be rescanned in color if a constant lighting source could be placed within the tunnel systems. The data are accurate enough to be used as guides for the rendering of features as line drawings and were used as such for the finds at the Temple of the Night Sun (Houston et al. 2015). This is important since the lidar provides contextual precision while still allowing for the creation of familiar styles to which archaeologists are accustomed. The greatest strength of the lidar data, however, is the ability to convey the three-dimensional relief of the monu-

FIGURE 9. Close-up of the tomb chamber for Burial 16 viewed from the exterior; cavities that held wooden beams can be seen coming out of the vault.

mental art (Figures 6 and 7; Supplemental Figures 1 and 2) that is either distorted by photography (compare to Figure 2b) or flattened in drawings (compare to Figure 5).

Conveying Tunnel Networks

The distilling of labyrinthine tunnel excavations into a series of two-dimensional plan and profile drawings can actually hinder interpretation by independent investigators. It is often impossible to present every section, and so decisions are made regarding which perspectives will be published. The engineers documented 87.1 m out of a possible 111.8 m (77.9 percent) of excavated tunnels beneath El Zotz Str. M7-1. Two lateral tunnels, totaling 7.8 m in length, used to investigate the earliest platform beneath the pyramid (Str. M7-1-Sub-1) were backfilled in 2013 before the current program was initiated. In addition, 16.9 m of new excavations examining the front of the earliest pyramidal form (Str. M7-1-2nd) beneath Str. M7-1 were begun after the engineers departed the field during the 2014 season. However, the completeness of the lidar documentation also enabled the backfilling of 16.7 m of existing tunnels on top of the Accession Platform (Str. M7-1-Sub-2), providing more stability within the tunnel system.

The lidar model is able to easily convey the complexity of the tunnel system beneath Str. M7-1 (Figure 8; Supplemental Figure 3). As an example, features such as the looted royal tomb are easily distinguishable, and the scan conveys the three-dimensionality of that burial chamber much better than looking at the plan and profile views in tandem. The relationship of the tomb and its vaulted access chamber to the central mask of the Accession Platform is clear, despite a minor resolution gap in the data. One can even see the holes where perishable wooden support beams were once in place to support the tomb's vault (Figure 9). The model was also instrumental in documenting the chamber of Burial 25, which could be accessed only through a small aperture and was therefore difficult to record using traditional methods.

Creating a Virtual Tourist Experience

One of the main benefits of the lidar documentation of archaeological tunnel systems is the ability to create a "virtual dig" for members of the public and scholarly communities. Using software designed at UCSD, videos of walkthrough tours through the excavation can be recorded (Figure 10; Supplemental Video; Petrovic et al. 2014). This powerful visualization tool allows others to experience the thrill of excavation and discovery in the comfort of labs, classrooms, and museums. This has the added benefit of protecting the archaeological features. Limiting the number of people who come into contact with the delicate, ancient modeled stucco architecture at El Zotz is critical to its long-term conservation.

DISCUSSION

In an important recent review of digital technologies, John Rick notes that "the potential to more accurately represent reality is a driving force in digital analysis and illustration" (Rick 2012:416). However, he also cautions that the adoption of costly digital devices can have an isolating effect if the technology is not accessible to others (Rick 2012:417) and that the transition to increasingly automated documentation equipment puts at risk the role of manual illustration in archaeological discovery and interpretation (Rick 2012:414). We will attempt to address these concerns here.

First, the issue of cost is an important one, both financially and in terms of necessary expertise. Generating 3D models is becoming accessible to everyone through the use of relatively simple apps for iOS™ and Android™ devices, many of which use some version of Augmented Reality (AR; Schmalstieg and Wagner 2007). However, large, sophisticated 3D models, like the one made for the Str. M7-1 tunnels, still require expensive equipment and substantial digital expertise that is not part of standard archaeological training. Creative interdisciplinary collaboration is the key to implementing cutting-edge technology in archaeology. In the case of the work presented in this study,

FIGURE 10. Still image of the interior of the Lidar model of Str. M7-1. The architectural step that connects the two masks of the Accession Platform is clearly visible on the left side of the image. Two of the tracking balls used to stitch the Lidar scans together are visible on the floor.

the collaboration provided benefits to both the archaeologists and engineers involved. The archaeological benefits are the focus of this article, but the Engineers for Exploration Program gained invaluable experience for a variety of graduate and undergraduate students who were able to contribute both in the field and lab settings. Having real world applications is critical for engineering students so that they learn to think outside their labs. The types of equipment necessary for 3D documentation can be found at many large research universities, but they are unlikely to be found in an anthropology department. Archaeologists need to broaden their interdisciplinary relationships to include collaborators with technological expertise in the same way that they engage with environmental scientists, epigraphers, and any other range of specialists to gain a more holistic understanding of the past.

Rick's second critique relating to the role of illustration in discovery cannot be dismissed. Excavating tunnels reveals snapshots of earlier building phases, and a great deal of interpretation is necessary to properly understand the archaeological context. Even more difficult is when the archaeologist is left with the scar of a long-abandoned looter's tunnel, which must be salvaged to recover as much information as possible. Part of this process of recovery is drawing the profile, stone by stone, forcing a level of concentration that can lead to insight about the building's construction sequence and generate ideas for future exploration. Barbara Fash, in discussing the documentation of monuments, writes, "[p]erhaps no longer relied on as accurate copies, manual illustrations still provide a superior method of learning about, and mentally recording, a monument" (Fash 2012). The same can be said for documenting a tunnel. The solution, it seems, is not to replace traditional documentation with digital modeling, but rather to use both to complement to one another. The 3D lidar model provides the most technically accurate representation of Str. M7-1's tunnel system and is certainly the best way to convey the excavations to the public. However, details such as the faded paint swirl in *Ux Yop Huun's* left eye on the northern mask of the Accession Platform were expertly recorded by Mary Clarke (Figure 5) and cannot be detected in the lidar data. Redundancy in documentation is beneficial. The lidar scanning of Str. M7-1 took two days of fieldwork and did not interrupt excavations. Profile and plan drawing is a more prolonged process, even when the slow pace of tunneling excavations provides time for such activities. By having both documentation methods in place, there are more options for presenting interpretations.

CONCLUSION

The archaeological tunnel is perhaps the most difficult excavation context to dig, interpret, document, and present. The use of a FARO™ Focus 3D 120 Scanner to document these complex systems at the Maya site of El Zotz produced incredibly detailed models that help to overcome some of the limitations inherent in traditional photography, plan, and profile renderings. The data have allowed archaeologists to isolate important archaeological features and thoroughly record their three-dimensionality for posterity. They also convey the true structure of the tunnel systems at El Zotz and can even provide the public with an opportunity to remotely "visit" excavations as a virtual experience. The effective use of 3D models in archaeology requires increased collaboration with colleagues specializing in digital technologies and results that are presented in tandem with traditional recording methods to provide the most complete record for possible interpretations.

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Data Availability Statement

The digital data acquired for this project are housed at the University of California, San Diego, at the following location: http://e4e.ucsd.edu/maya-archeology-point-clouds. These are point clouds for the tunnels in Structure M7-1 and El Diablo (Temple of the Night Sun).

Supplemental Materials

Supplemental materials are accessible via the SAA member login at www.saa.org/members-login:

Supplemental Video 1: Walkthrough of the tunnel system in Structure M7-1.

Supplemental Figure 1: Manipulable model of the Chahk mask from the Temple of the Night Sun.

Supplemental Figure 2: Manipulable model of the architecture of the Accession Platform (Str. M7-1-Sub-2).

Supplemental Figure 3: Manipulable model of the tunnel system beneath Structure M7-1.

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