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UNIVERSITY OF CALIFORNIA, SAN DIEGO

**Terrestrial Laser Scanning and Archaeology: Developing New Methodologies for  
Landscape Visualization and Analysis**

A Thesis submitted in partial satisfaction of the requirements for the Master of Arts

in

Anthropology

by

Ashley M. Richter

Committee in charge:

Professor Thomas E. Levy, Chair  
Professor Geoffrey E. Braswell  
Professor Guillermo Algaze

2014

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The Thesis of Ashley M. Richter is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

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Chair

University of California, San Diego

2014

## DEDICATION

In recognition of her continued support and encouragement, I dedicate this thesis to my mummy dearest, Sophia.

## EPIGRAPH

*Inceptis grauibus plerumque et  
magna professis  
Purpureus, late qui splendeat,  
unus et alter  
adsuiter pannus, cum lucus et ara Dianae  
et properantis aquae per amoenos  
ambitus agros  
aut flumen Rhenum aut pluuius  
describitur arcus;  
sed nunc non erat his locus. Et  
fortasse cupressum  
scis simulare; quid hoc, si fractis  
enatat exspes  
nauibus, aere dato qui pingitur?*

– Horace, *Ars Poetica*, (Lines 14-21).

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## LIST OF ABBREVIATIONS

CalIT2	-The California Institute of Information Technology and Telecommunications
CISA3	-The Center of Interdisciplinary Sciences for Art, Architecture and Archaeology
ELRAP	-The Edom Lowlands Regional Archaeological Project-the University of California, San Diego's Middle East Archaeological Field School in Southern Jordan
IGERT-TEECH	-Integrative Graduate Education and Research Traineeship for Training, Research, and Education in Engineering for Cultural Heritage Diagnostics
LiDAR	-Light Detection and Ranging
NSF	-The National Science Foundation
SCS	-Sediment Intervals and Site De-Formation Processes: Exploring Time Lapse Laser Scanning Capabilities and Methodologies for Archaeology (also known as Sand Castles for Science)
UCSD	-The University of California, San Diego

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Chapter 2.1 and Case Studies 2.1a and 2.1b, in part, are an abbreviated version of the material as it appears in Richter, A.M., Kuester, F., Najjar, M., and Levy, T.E., 2012. Terrestrial Laser Scanning (LiDAR) as a Means of Digital Documentation in Rescue Archaeology: Two Examples from the Faynan of Jordan. Proceedings of the 18th *IEEE Virtual Systems and MultiMedia (VSMM), Milan 2012*. The thesis author was the primary investigator and author of this paper.

## VITA

- 2007 BA Joint Honours Archaeology and Ancient History, Durham University, UK
- 2009 Content Creation Researcher for CyArk (a non-profit foundation devoted to the creation and archiving of LiDAR point clouds of cultural heritage monuments)
- 2009 Excavator on ELRAP, Jordan
- 2011 MA Archaeology and Heritage, University of Leicester, UK
- 2011-2014 National Science Foundation IGERT-TEECH with CISA3 based at CalIT2 at UCSD as part of the MA/PhD program in Anthropological Archaeology
- 2011 LiDAR Technician Cyprus ArchaeoMetallurgical Project (CAMP)
- 2011 Staff on ELRAP, Jordan
- 2012 Staff on ELRAP, Jordan
- 2012 LiDAR Technician on American Center of Oriental Research's Temple of the Winged Lion Conservation Project.
- 2013 UCSD Graduate Student Association Interdisciplinary Research Award Winner
- 2013 National Science Foundation IGERT Video & Poster Judge's Choice Winner
- 2013 Project Coordinator, Media & Outreach Officer, LiDAR technician and Researcher on the CISA3 Italy Field Season for projects with the University of Calabria, the Baptistery of St. Giovanni, & Palazzo Vecchio
- 2014 MA Anthropological Archaeology, University of California, San Diego



## PUBLICATIONS

- Richter, A.M., Petrovic, V. Angelo, R., Seracini, M., and Kuester, F., 2014. From STEM to STEAM: Aerospace Partnerships with Cultural Heritage Diagnostics. IEEE Aerospace, Big Sky, Montana.
- Richter, A.M., Petrovic, V., Vanoni, D., Parish, S. and, Kuester, F., 2014. Digital Archaeological Landscapes and Replicated Artifacts: Questions of Analytical and Phenomenological Authenticity & Ethical Policies in CyberArchaeology. UNESCO ICOMOS IEEE Digital Heritage Congress, Marseilles, France.
- Srouf, D., Richter, A.M., Levy, T.E., and Kuester, F., 2014. Temporal Terrestrial Laser Scanning to Visualize the Excavation Process. UNESCO ICOMOS IEEE Digital Heritage Congress, Marseilles, France.
- Levy, T.E, Tuttle, C.A., Vincent, M.L.\*, Howland, M., Richter, A.M.\*, Petrovic, V.\*, Vanoni, D.\* & Kuester, F. (2014) The 2012 Petra Cyber-Archaeology Cultural Conservation Expedition: Temple of the Winged Lions and Environs, Jordan. *Antiquity*, 87,(335).
- Richter, A.M., Kuester, F., Najjar, M., and Levy, T.E., 2012. Terrestrial Laser Scanning (LiDAR) as a Means of Digital Documentation in Rescue Archaeology: Two Examples from the Faynan of Jordan. *Proceedings of the 18th IEEE Virtual Systems and MultiMedia (VSMM), Milan 2012.*
- Levy, T.E., Najjar, M., Gidding, A.D., Jones I.W.J., Knabb, K.A., Bennalack, K., Vincent, M., Novo Lamosco, A., Richter, A.M., Smitheram, C., Hahn, L.D., and Balaswaminathan, S., 2011. The 2011 Edom Lowlands Regional Archaeology Project (ELRAP): Excavations and Surveys in the Faynan Copper Ore District, Jordan. *Annual of the Department of Antiquities of Jordan*. The dissertation author was the primary investigator and author of her section of the paper.

## PRESENTATIONS

*IEEE Aerospace, Big Sky, Montana. March 2014. From STEM to STEAM: Aerospace Partnerships with Cultural Heritage Diagnostics.*

*Higher Experiential Learning Conference. University of California, San Diego. January 2014 Re-Evaluating Diagnostics Undergraduate Internship: New STEAM Pathways towards Interdisciplinary Collaborative Research in Cultural Heritage Diag*

*UNESCO International Digital Heritage Congress, October 2014. Digital Archaeological Landscapes and Replicated Artifacts: Questions of Analytical and Phenomenological Authenticity & Ethical Policies in CyberArchaeology.*

*Virtual Archaeology, Museums, and Cultural Tourism, Delphi, Greece, September 2014. "Finding Meaning in the Data Avalanche: The Ethical Dangers and Community Values of Digitizing the Past."*

*University of California, Los Angeles' Cotsen Institute of Archaeology June 2014-Workshop Director: "Capturing Archaeological Sites & Artifacts in 3D for Archaeological Analysis & Cultural Heritage Dissemination"*

*University of California, Los Angeles' Cotsen Institute of Archaeology June 2014-Series Guest Lecturer: "Integrated Data Capture Technologies and Methodologies for Rapid Archaeological Field Deployment and the Creation of Point Cloud Based Data Scaffolds for Cultural Heritage Dissemination: Case Studies from Cyprus, Italy, Jordan, and San Diego"*

*Theoretical Archaeology Group Conference, University of Chicago May 2014: "Expanding Layered Realities: Cognitive Annotated Imaging Systems for Accurate Archaeological Visualizations and Augmentations of Space and Time in 3D Immersive Virtual and Physical Environments for Collaborative Research and Public Dissemination"*

*University of California, San Diego Graduate Student Association Award Gala May 2014: "Visualizing the Past for the Present: Archaeology in an Interdisciplinary Age."*

*IEEE Virtual Systems and Multimedia Milan September 2014: "Terrestrial Laser Scanning (LiDAR) as a Means of Digital Documentation in Rescue Archaeology: Two Examples from the Faynan in Jordan"*

*High-Tech Heritage: How Are Digital Technologies Changing our Views of the Past? The Center for Heritage and Society, University of Massachusetts, Amherst. Friday, May 4, 2012. Point Cloud Visualizations as a Heritage Education Tool among the Local Tribes in the Wadi Faynan region of southern Jordan.*

## FIELDS OF STUDY

### Studies in Levantine Archaeology

Professor Thomas E. Levy, Department of Anthropology at the University of California, San Diego 2011-2014

### Studies in Laser Scanning and Point Cloud Visualization Systems

Professor Falko Kuester, Department of Computer Science and Engineering at the University of California, San Diego 2011- 2014

Professor Maurizio Seracini, Department of Structural Engineering at the University of California, San Diego, 2011-present

### Studies in Public Archaeology and Archaeological Theory and Methodology

Professor Margarita Diaz-Andreu, Department of Archaeology at Durham University, UK 2004-2007

Professor Mark Pluciennik, Department of Archaeology and Ancient History at the University of Leicester, UK 2009-2011

Professors Geoffrey E. Braswell, Guillermo Algaze, and Paul Goldstein, Department of Anthropology at the University of California, San Diego 2011-present

### Studies in Roman History and Archaeology

Professors Ted Kaizer and Clemence Schultze, Department of Classics and Ancient History at Durham University, UK 2004-2007

Professor Richard Hingley, Department of Archaeology at Durham University, UK 2004-2007.

ABSTRACT OF THE THESIS

**Terrestrial Laser Scanning and Archaeology: Developing New Methodologies for  
Landscape Visualization and Analysis**

by

Ashley M. Richter

Master of Arts in Anthropology

University of California, San Diego 2014

Professor Thomas E. Levy, Chair

The development and availability of capable point cloud software creates a new archaeological forefront in landscape point-cloud data-capture and visualization. Terrestrial scanning via Light Detection and Ranging (LiDAR) can therefore be a worthwhile diagnostic tool for field archaeology if efficient methodologies for overcoming its mechanical, time, and processing limitations can be established. This thesis investigates the viability of terrestrial LiDAR for field archaeological purposes, and outlines a new methodology by which its limitations can be overcome and it can be effectively used for archaeological data capture in harsh environments under time constraints.

Building off of the success of the efficient data collection and processing methodologies created to resolve the scanner's limitations, this thesis will then explore areas of archaeology where landscape point clouds and expedient digital

documentation might be used (i.e. Rescue LiDAR and temporal scanning), utilizing test case studies in southern Jordan. The integrated laser scanning methodology presented here is intended to solve three problems—one technical, one anthropological, and one educational. In streamlining methodologies, a digital conservation workflow for archaeological and world cultural heritage field sites is established. With the ability to preserve endangered data and return it to the lab, a myriad of anthropologically significant data which would be impossible to discern in the field can be gleaned. In this thesis, various ways in which point cloud models may be subjected to quantitative analysis to study will be indicated. Furthermore, the capacity of point clouds for public archaeology purposes, phenomenological perspective, and educational dissemination will be discussed.

## INTRODUCTION

In the 2012 blockbuster film *Prometheus*, the scientists of a space exploration send off two flying spheres which rapidly traverse an unknown planetary landscape, wirelessly sending back a spatial point cloud for the scientists to use as a three-dimensional map. Alas, this is just a bit of movie magick. Such portable, speedy, remote laser scanning technologies do not yet exist for surveying. Indeed, what is little realized about laser scanning is the difficulty with which such point clouds are collected and processed, particularly via terrestrial light detection and ranging or LiDAR laser scanning systems. The practicalities of utilizing such temperamental equipment, coupled with the inability to nimbly process and manipulate large point cloud data sets, has relegated terrestrial LiDAR to specialized fields of industrial surveying and the cultural heritage digital documentation of monuments. Heretofore, utilizing terrestrial LiDAR for surveying a detailed and subtle archaeological landscape would have been an inefficient use of resources. Aerial LiDAR, despite its expense and incapability to create a highly detailed record of ground features, would have been the best alternative technology for these purposes (Chase et al. 2012; Heinsol & Sitter 2010; Risbøl 2010:105, 110).

Nonetheless, recent programming innovations at the University of California, San Diego (UCSD) California Institute of Information Technology and Telecommunications (CalIT2)'s Center of Interdisciplinary Sciences for Art, Architecture, and Archaeology (CISA3) have led to a processing and visualization solution for large data sets (Levy et al. 2010, Petrovic et al. 2011). CISA3 computer science and engineering researcher Vid Petrovic's program Visicore can manipulate billions of data points as opposed to previous software, such as Leica's *Cyclone*, which tend to have difficulties after approximately twenty five million points. As part of CISA3, Mr. Petrovic is designing his software to not only

handle archaeological point clouds, but to have the ability to annotate these clouds with further archaeological data, thus creating an archaeological scaffold that can be used for diagnostic and dissemination purposes. With the ability to do something meaningful with large data sets, the question became, how then could large archaeological data sets be acquired given the limitations of laser scanning equipment? And furthermore, what aspects of efficient laser scanning could then be harnessed to further aid archaeological documentation, analysis, and dissemination? Archaeology is not just the study of man and his material culture and share that information with others. It is also the investigation of how we go about studying man and his material culture and share that information with others. In order to study the ancient landscape, and share our knowledge with others, archaeologists need to have working methodologies that collect data and disseminate their resulting interpretations. In this respect, technology like terrestrial LiDAR is a vibrant new building block of the archaeologist's structuralist quest to understand and explain the history of mankind.

This thesis will present several methodological and equipment solutions created to acquire large data sets concerning archaeological landscapes. It will further address several archaeological purposes towards which laser scanning can be used now that high resolution landscapes can be acquired via terrestrial laser scanning. The acquisition of digital landscapes is of fundamental importance to analyzing the context of archaeological sites and how ancient mankind interacted with each other (Crumley and Marquardt 1990:78-79; Harmon et al 2006) and with their environment (Balee and Erickson 2000; Erickson 2010). Terrestrial LiDAR can therefore be used as a hermeneutic digital documentation tool. As such, this thesis broaches the notion that the newly field efficient terrestrial LiDAR can be used to aid in the digital documentation of rescue archaeology projects (i.e., 'Rescue LiDAR') and that sequenced scans of an on-going excavation ('temporal scanning') can be utilized to

create a highly detailed record of the site destruction which archaeological excavation aims for. These records of digital spaces serve not just as reflections of the ancient world, but also as representatives of modern work into the study of the past. Given the captivating visualization capabilities of terrestrial LiDAR, which go well beyond those of typical GIS tools, there is further capability and incentive for point cloud data to be published and meaningfully accessed by a more interested public (Llobera 2000;12-123, 132). Thus, given field archaeology's long established goal of recording the material record with as much detail as possible (Renfrew and Bahn 2009), the 'Rescue LiDAR' platform introduced here brings the archaeologist's tool box into the 21<sup>st</sup> century taking full advantage of increasingly powerful computer hardware and software.

The majority of field-work to test the various methodologies and equipment changes created for this project were integrated into the digital data collection projects of UCSD Edom Lowlands Regional Archaeological Project (ELRAP) and were therefore conducted in southern Jordan during the course of the 2011 and 2012 field seasons. Awareness of problems that needed to be overcome were generated primarily from the author's own experiences with laser scanning for cultural heritage and as an assistant to Tom Wypych during the initial use of laser scanning in the field on ELRAP in 2009. Mr. Wypych also offered insight, advice, and eventually a solution into potential power issues that might arise in the field.

Additional testing of methodologies was carried out over the summer of 2012 under the auspices of Sediment Intervals and Site De-Formation Processes: Exploring Time Lapse Laser Scanning Capabilities and Methodologies for Archaeology (also known as Sand Castles for Science or SCS), a mini-grant project managed by the author and funded by the National Science Foundation (NSF) as part of the Integrative Graduate Education and Research



Traineeship for Training, Research, and Education in Engineering for Cultural Heritage Diagnostics (IGERT-TEECH) program with which the author is affiliated through CISA3, CalIT2 and UCSD.

## CHAPTER ONE

### Terrestrial Laser Scanning for Field Archaeology: Limitations & Solutions

#### 1.1 Terrestrial Laser Scanning: A Brief Introduction

In order to explain the limitations of laser scanning in the field and therefore elucidate both the solutions reached to negotiate the process and the archaeological aspects to which the newly efficient LiDAR might be applied, a brief overview of laser scanning is required.

Light Detection and Ranging is a remote sensing tool which uses a time of flight algorithm on a pulse or phase-based optical laser beam to calculate the three-dimensional geospatial position of the coordinates representing the space in its field of view. This creates a virtual model of the given space reconstructed digitally from these points. This model is therefore known as a point cloud, an occasionally confusing term given the prevalence of other wireless 'cloud' technologies omnipresent in current pop culture tech.

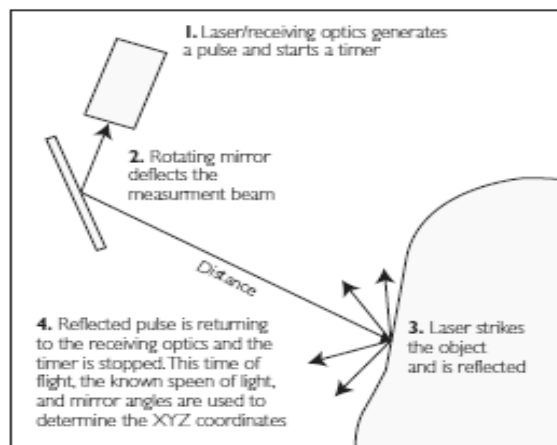
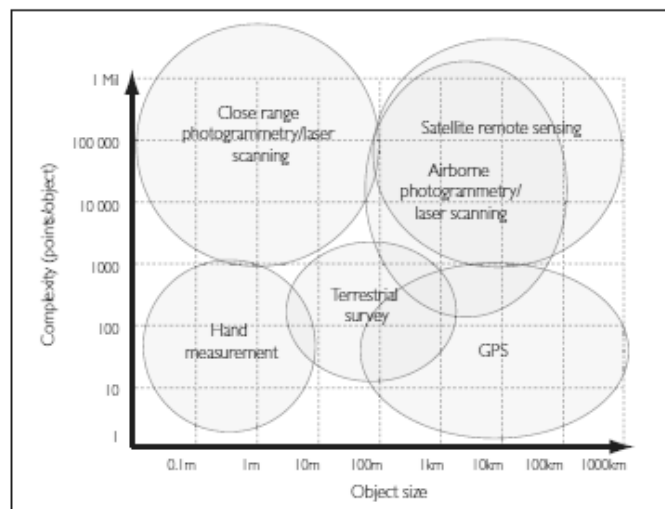


Figure 1: A diagram elucidating the functionality of a standard laser scanner. From Barber and Mills 2007:18.

The density of the point cloud is determined by the scanner's highest resolution capacity and by the user, who controls both the spacing of the points and the intensity range of the laser (and therefore the distance of accurate measurement the point spacing holds up over). The length of time it takes to obtain the scan is determined by the length of the range and the proximity of the points to each other. Therefore a high density scan of a large area takes a very long time to scan. Aerial LiDAR, i.e. laser scanning applied from a low-flying plane, therefore creates a low density point cloud at a long range This can provide valuable overviews of archaeological landscapes. However, for detailed diagnostic purposes and certainly for the viewing of smaller facets of archaeological landscapes, such as excavation trenches, higher resolution point clouds taken from a ground level perspective are necessary if possible to obtain. As noted in the graph below, close range photogrammetry/laser scanning is capable of acquiring data at a complex detail range which the majority of other digital documentation methodologies cannot reach. The purpose of this survey was to operate at the farthest right edge of the terrestrial laser scanning circle.



Graph 1: Comparative Documentation systems. From Barber and Mills 2007:1.

In order to create an explorable point cloud from terrestrial LiDAR, free of significant data gaps (known as laser shadows), multiple scans must be taken from various proximal locations and combined together in post-processing. This aids in the elimination of the large circular laser shadow left were the scanner is positioned and attempts to fill in all sides of objects in view. In this respect, the placement of the laser scanning stations to thoroughly collect a decent point cloud of a given space is a mathematical art form which requires foresight into the prospective visualization and comprehensive understanding of what will be captured within the scanner's field of view at a given resolution and range.

The scans can be combined into a large conglomerate point cloud either digitally or manually via the recognition of targets placed within the landscape at the time of scanning. The process whereby scans are combined is known as 'registration.' Given that each scan is often representative of millions of data points, a combined point cloud can be quite large. Please note that for archiving or minute measurement purposes, the digital space created by the data set need not be easily manipulatable. But if it is to be used for wider

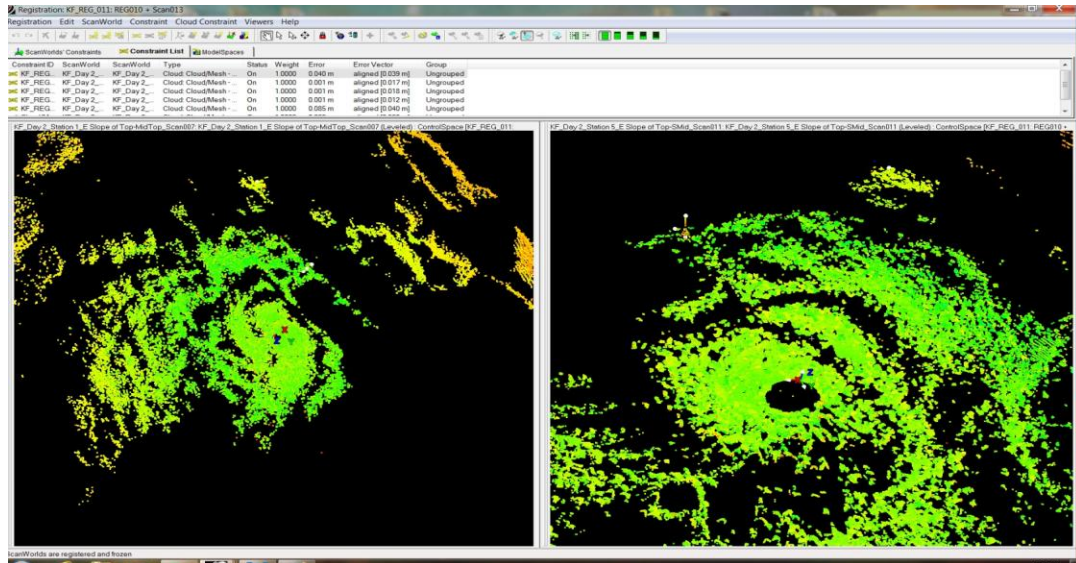


Figure 2: The Registration navigator of Leica's proprietary scanning software Cyclone. The singular point cloud on the right is being added to the conglomerate point cloud of Khirbat Faynan on the left. Note the central circular laser shadow in the right hand point cloud. This is the missing data lost to the scanner's position in every scan.

archaeological analysis or digital dissemination or tourism, it needs to be accessibly explorable. It is this facet of efficient and smooth control which CISA3's Vid Petrovic has contributed to point cloud rendering software. He and the author are currently collaborating on further post-processing and annotating capabilities towards speeding up point cloud processing and dissemination capabilities, some of which will be touched upon throughout the paper.

It should be noted prior to engaging in the solutions which were created to aid in creating an efficient methodology for use, that each model of laser scanner is slightly different and brings with it its own slew of additional problems depending on its design, processing capabilities, and associated software. Of the two scanners available for testing at CalIT2, the Faro Focus 3D and Leica ScanStation 2, the Leica ScanStation 2 --as both the older and more field and temperature durable model--was deemed most appropriate for

archaeological field use in the desert conditions of southern Jordan. Where appropriate, ScanStation 2 only problems have been noted in the text.



Figure 3: The Leica ScanStation 2 deployed in the field in Jordan in 2011. Image by the author.

## 1.2 Terrestrial Laser Scanning for Field Archaeology

Terrestrial LiDAR is plagued by a variety of issues which make it difficult to deploy rapidly for field archaeological purposes, particularly in the arid, hilly region of southern Jordan where the majority of recent archaeological work at CISA3 has focused. The most salient among these problems being that scanning is a time consuming and labor intensive process. Therefore, in order for scanning to be a useful form of digital documentation, the means of deploying the scanner needed to be streamlined and the methodology of collecting the data needed to be altered to focus on the time sensitive nature of the task. In other

words, what can be done to the scanner and the scanning process which would result in the best data in the least amount of time? It has often been the case that technology developed for other disciplines needed to be adapted before effective archaeological use (Zubrow, 1990:68-69), in this terrestrial LiDAR is merely the newest challenge.

From an archaeological perspective, the most crucial of the problems which deters efficient use of LiDAR in the field are problems regarding its field of view. Scanners are blind towards the area directly below them, which means that every scan has a circular laser shadow at its center. The scanner's blind-spot extends downwards in a cone which means elements of interest which fall into this laser shadow will not be captured. In terms of the archaeological phenomena that LiDAR is meant to record in the field, this is a particular problem. This means that when placed on the edge of a precipice, for instance the edge of an archaeological trench or test pit, the scanner will not collect some of the most significant pieces of data in each scan (as shown in Illustration 1). Likewise, if placed in a small room with low walls or other confined space, virtually none of the relevant data would be collected within the actual space (as shown in Illustration 2). A vast conglomerate of scans from a distance would therefore be needed to capture a point cloud of a simple trench or small room from above and around the edges. If, however, the scanner's height and angle of its field of view could be adjusted, fewer scans would be needed per relevant feature.

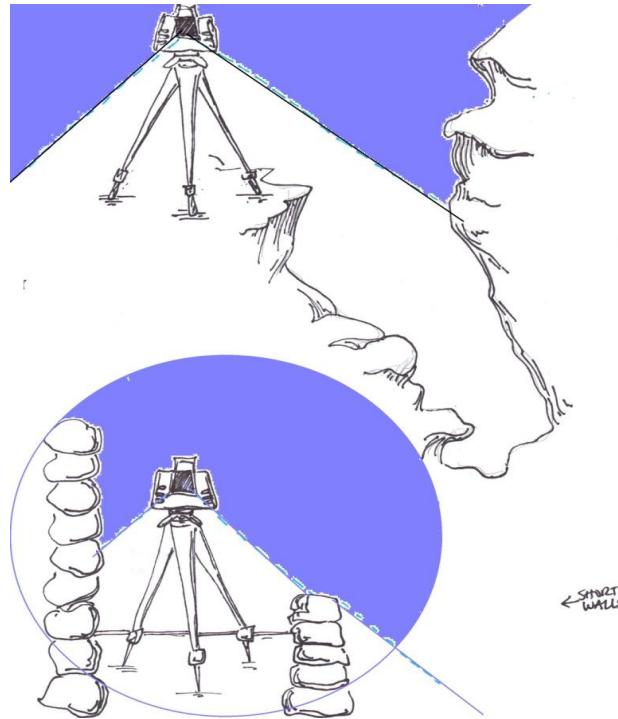


Illustration 1A & 1B: Illustration 1A at the top depicts the scanner on the edge of a precipice encountering field of view issues looking downwards. The shaded area represents what the scanner can see and therefore capture relevant data on. Illustration 1B at the bottom depicts the scanner placed in a confined area featuring a short wall-a common architectural occurrence on an archaeological site. Again, the shaded area represents those spaces that would be cast into laser shadow utilizing typical scanning methodology

### 1.3 The Inclusion of the Quadropod

Because of the weight and vibration issues of its scanner, Leica recommends that the ScanStation2 be utilized only with a standard surveying tripod. Such tripods are quite tall but can have their height increased or decreased as needed by repositioning the extension of the legs or the placement of the tripod feet respectively. Unfortunately decreasing the height of a standard surveying tripod decreases the stability of the tripod -a necessity when an expensive piece of heavy equipment is placed on it. It would also mean that the splayed legs which are necessary for decreasing the height of the tripod would be visible in every scan. More important to our purposes, however, it means that the wide-splayed scanner would not be usable on the edges of precipices or in confined spaces-it simply wouldn't fit.





Figure 4A and 4B Figure 4A at left depicts a standard Leica surveying tripod. Image courtesy of Leica Geosystems. Figure 4B depicts the head of the Novoflex Quadropod. Image courtesy of Novoflex.

Therefore, commonsensically, another surveying tripod was needed. After much sourcing, the sturdy Novoflex Quadropod was acquired as a solution. Capable of bearing up to one hundred pounds, it is able to bear the Leica Scanstation2's 40+ pounds without significant vibration issues. The standard screw socket of the quadropod was not, however, intended for the tribrach upon which the Scanstation2 sits. And so a special screw connection was fashioned by CallT2 engineers to adapt the quadropod to our purposes. Now, at least, the scanner could be placed in confined quarters and still get data. Not only would it lessen the number of scans required to get coverage of an archaeological site, it often captured data that would have been impossible to get utilizing the standard surveying tripod recommended for use by the manufacturer. Capable of standing 'scanner strong' at one to five feet (and lower if splayed), using the quadropod with the scanner also reduces the standard scanner station laser shadow in each scan by approximately half the average

diameter from when the standard surveying tripod was used. Specific successes with the quadropod will be discussed in later sections.

#### 1.4 The Creation of the Tilt Head

However, the quadropod still did not resolve that most pivotal of problems- how to rapidly scan archaeological trenches from their sides. The most functional approach to this would be to rig up a system whereby the scanner could tilt downward. Such a tilted scan would mean that the x and z planes would be severely tilted in the point cloud. However, this would be reconcilable to other scans taken at a level standing during processing. Given the sensitivity of the scanner, however, this had not previously been accomplished. In spite of this, a thorough investigation of the machine's capabilities yielded the fact that it could be used aboard a moving ship if its dual axis compensator was disabled. The dual axis compensator secures the level plane of the scanner and disengages the device should the scanner become unlevelled (thereby interrupting the scanning process). It was therefore feasible that if it could be disabled to work on a seagoing vessel and therefore be disabled to function at a slight tilt in a moving environment, that it might work at a full tilt in a still environment.

With the aid of CallT2 machinist Daniel Johnson, a device was designed and crafted which could be placed in-between the tripod and the tribrach which would effectively tilt the scanner a full forty five degrees or at lesser graduations thereof, depending on the placement stability of the tripod in use in a given environment. This device, dubbed 'the Tilt Head,' allowed the field of view to increase exponentially at precipices, in that it not only looks downward, it casts the scanner's laser shadow upward and back, often into sky, meaning fewer scans are needed to collect data at such sites. The tilt head allowed

archaeological trenches to be thoroughly scanned in as few as two scans and provided visibility into deep areas which would otherwise be outside the ken of the scanner entirely. Specific successes with the tilt head will be discussed later.



Figure 5: The Tilt Head is displayed in action, poised between a surveying tripod and the tribrach and scanner in the field in Jordan. Image by author.

### 1.5 Further Equipment & Record Keeping Modifications

While the quadropod and tilt head are universal modifications that can conceivably be utilized on a variety of scanners in similar situations, several updates to the field equipment for the ScanStation 2 needed to be carried out prior to fieldwork in order to streamline its functionality for our purposes.

The Leica Scanstation 2 is meant to be operated via specialized lithium batteries. These, however, have a maximum operating capacity of four hours before they need to be recharged. This is an inconvenient time limit for a field day in the desert- where time is at a

premium to begin with and the cost of getting to a site is more worthwhile if a large part of the day is spent there. However, as replacement lithium batteries were economically unavailable, various systems utilizing alternative forms of power were experimented with. These ranged from the batteries of the field car to a generator. But the daily mainstay of the field equipment was eventually a pair of heavy deep cell batteries which had to be charged nightly at the field lab. As a direct connection between any of these power sources and a sensitive piece of equipment like the laser scanner would not provide a clean enough power source, a series of inverters were applied as a go-between to smooth out the sine wave of the power connection. Two commercial models were tested over the 2011 ELRAP season, and though adequate for power purposes, contributed approximately 15 pounds of further weight to the field set up. For the 2012 ELRAP season, CISA3 computer science and engineering researcher Tom Wypych built a powerful one pound inverter for the LiDAR gear which both provided capable, clean power, and further lightened the field load. Not only did it remove the heftier inverters from the weight tally, its direct connection to the scanner's hot swappable input, meant that the 3.5 pound AC power plug adapter brick which comes with the regulation scanner was bypassed and therefore could also be removed from the field equipment retinue. This is also significant, in that the desert conditions and gritty sand can easily ruin cable connections, and therefore, the fewer connections that need to be made at each scanning set-up, the less likely additional damage is to occur to the equipment.

Additionally, a thorough investigation into good scanning practices was undertaken to create a metadata collection format and file naming system for standardizing the processing and archiving systems (Aimsworth et al 2007; Barber and Mills 2007; Bradley

2006; Bryan, Blake and Bedford 2009; Hammer 2000; and Palmer et al 2009). This resulted in the creation of a metadata worksheet for each scan, as shown below in Illustration 3.

<b>Day #</b>	<b>Site Name</b>	<b>Station #</b>	<b>Scan #</b>
			<div style="border: 2px solid black; padding: 10px; text-align: center;"> <b>Sketch of Scanner &amp; Target Placement with regards to local features</b> </div>

Illustration 2: The format for the scanning metadata worksheet created as part of the workflow for terrestrial LiDAR in the field. An example of this filled in worksheet culled from the 2011 metadata notebook is available in Appendix A.

## 1.6 Alterations to Scanning Methodologies

With the field equipment now geared towards archaeologically specific data collection and an archival format in place, it was also prudent to re-evaluate the actual scanning format to streamline it to our purposes as well. Cultural heritage terrestrial laser scanning entails supra-high resolution scanning of smaller spaces or singular monuments. Industrial surveying using terrestrial laser scanning involves the low resolution scanning of larger spaces enhanced with occasional high resolution pockets. A mixture of these two- whereby large spaces were scanned at high resolution with occasional areas of supra-high resolution- is obviously the best case scenario.

Thus, a method typically employed for road surveying, free station scanning, was employed for our purposes. This entails traversing the landscape with a small series of targets which are constantly being replaced and are therefore not geo-referenced via each

individual target but via geospatially known features within the point cloud. Imagine, if you will, a single drop of paint on paper-the color is solid at the center of the drop, but possesses irregular edges splattering outward. In order to fully coat the paper in paint, the paper must be coated in droplets to fill in the splattered edges. Free-station scanning relies on the solid masses of point clouds to fill in the in-between spaces without having to traverse the whole space. Its geo-referencing system relies on specific knowable areas, for example, the corners of the page, being geo-referenced to provide a spatial coordinate system for the remainder of the metaphorical page of points.

Adapted for archaeology, free-station scanning means that conventional metal tripod targets with planar heads or paper targets can be used as short cuts to register data during processing but need not be used as the means of geo-referencing (or at all if there are significant features which can be used as targets in their stead). This means two things. One, the standing targets (each weighing approximately eight pounds and which take an average of five plus minutes to set up per scan) need not be used in the majority of scan work. And two, a total station and associated GIS specialist need not accompany the LiDAR contingent as it traverses over significant landscapes. Instead, only coordinates for specific spots which will be visible within the point cloud without significant placement error and associated metadata (i.e. an annotated photograph or other useful note-keeping system) need to be provided. A coordinate system for each conglomerate point cloud can therefore be created during registration using these few coordinates. Though free-station scanning was a success in collecting high resolution data of archaeological landscapes, the geo-referencing element is still in development stages. A workflow methodology for three-dimensional coordinate collection needs to be stabilized on the GIS end (Haciguzeller 2012; Howard 2007:7-72; Merlo 2004:278-279) . And meanwhile, a coordinate creation system is

being built into Visicore to streamline the geo-referencing of the point clouds without having to go through the proprietary scanning software. Leica, for instance, recently made this aspect of their computer program, *Cyclone*, a high cost additional update to their regular system as opposed to an included component, as had previously been the case.



Figure 6A and 6B: Aerial Photography of the large site of Khirbat Faynan, included here to illustrate the size of the initial landscape terrestrial laser scanning attempted (Photos courtesy: UCSD Levantine Archaeology Laboratory).

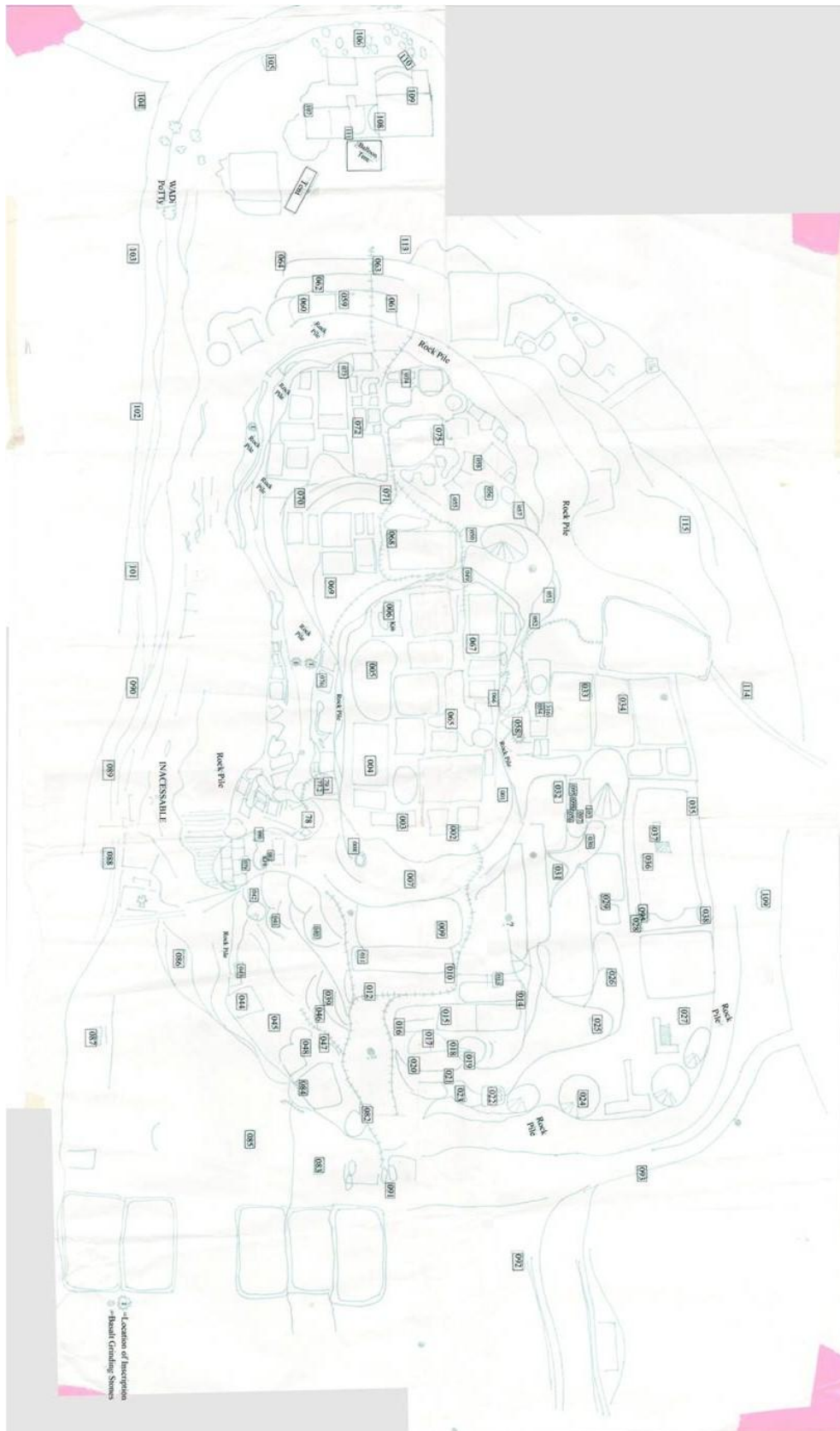


Illustration 3: The final terrestrial laser scanning survey map of Khirbat Faynan depicted the one hundred and thirty scans taken to collect a point cloud of the tell and its surrounding areas. This is representative of five billion+ data points and encompasses twenty-six days of field work.



In addition to GIS input to flesh out the point cloud for archaeological purposes, further contribution from photogrammetric aspects add significantly to the data collection process and eventual dissemination product. ELRAP is fortunate in that it was able to deploy both aerial photography and Structure from Motion over the 2011 and 2012 field seasons. Aerial photography provides useful contextual imagery for the point cloud landscape within virtual space. The low density point clouds created from Structure from Motion photography can fill in further details of the site and provide checks for the geospatial placement of elements within the high density point clouds created from terrestrial laser scanning (Smith et al 2011). Structure from motion point clouds created from aerial photography by new CISA3 colleague Matt Howland can also be utilized as a framework for the high density LiDAR point clouds; and where aerial point clouds exist, but no LiDAR data, as contextual clouds in digital space. As part of the 2012 season of ELRAP a workflow for collecting LiDAR data simultaneously with computational photography, including close-up photogrammetry for Structure from Motion and recognizable features for Augmented Reality technologies was established while working on ELRAP projects in Wadi Faynan in Jordan by the author and CISA3 colleagues Vid Petrovic and David Vanoni. It was immediately tested at a high-profile digital documentation project at Petra and resulted in a considerable chunk of data still undergoing processing. Indeed, the collaborative data collected from aerial photography and structure from motion are all still under development by other colleagues at CISA3 in conjunction with the terrestrial LiDAR point clouds collected with the new methodologies established for this project.

## CHAPTER TWO

### The Archaeological Purposes of Point Clouds

As will be shown here, the aim of creating point clouds for archaeological research is to provide a platform for incorporating a wide range of different datasets for spatial analyses. Thus far this thesis has focused on the technical adaptation of equipment and the acclimatization of its workflow to field archaeological purposes. The above adaptations were tested and found to be successful to speed up the digital documentation of archaeological landscapes via terrestrial LiDAR, thereby making it a viable technique of data acquisition for field archaeology. Combined with the computer programming innovations in visualizing large data sets of point clouds, UCSD's CalIT2, and CISA3 now have the capability to collect and disseminate point clouds of archaeological landscapes and finished excavations. The working goal of having this capacity is to use the point clouds as an archaeological framework or scaffold, upon which other archaeological data collected in the field could be added. If capable of being combined together in the field, this would thus produce a working diagnostic tool for archaeologists making surveying and excavation decisions. Beyond the field, this is an elegant visualization system for displaying archaeological data at varying levels of intensity and erudition?? for other archaeologists, thereby aiding in ecological and landscape theory approaches towards understanding spatial use and communication across distances, etc (Constantinidis 2004:258). Or the point clouds can be utilized for cultural heritage education or digital tourism purposes for the layman beyond the academic bubble (Campo 2004:192). But what else? With the availability of this new technology and visualization system-what other aspects of laser

scanning can be harnessed to enhance archaeological digital documentation? Having the capacity to use such technology for archaeology is inconsequential if not applied meaningfully towards the wider goals of the discipline.

## 2.1 Rescue LiDAR

Given that the focus of adapting laser scanning was to speed up the data collection process, one of the most valuable cultural heritage applications of an expedient terrestrial laser scanning system is towards rescue archaeology. When one encounters the term 'rescue archaeology' it typically conjures up urban images of progressive destruction paused for data collection. Such projects are usually undertaken when a legally mandated survey of archaeological potentiality or public outcry over heritage destruction has deemed it necessary. But what happens to those unfortunate archaeological sites where there is no law comparable to the United Kingdom's PPG16, which insists that the planning stages of building projects take archaeology into consideration? Or what if there is no public outcry over the destruction of obscure and isolated sites? How then are archaeologists to know to preserve them? This easily spirals into a philosophical argument. Parallel to the William James adage, if a tree falls in the woods and there is no one to hear it, did it make a noise? If an archaeological site disappears and there was no way to document it, then what?

It is a proverbial can of worms, one which will only be partially addressed here. However, there are opportunities where such neglected sites, slated for destruction and whose heritage significance is overlooked locally, might be encountered and rescued for the archaeological record. There are those rare occasions where archaeologists already in the field, working on a planned excavation, hear rumors of nearby site destruction and can do something about it. Granted, given the time and financial limits of an already on-going

excavation, often these efforts will, of necessity, be limited. But, something is always better than a lot of nothing. If the site is destroyed without documentation of any kind, the site, which had considerable potential to contribute to the archaeological record, becomes virtually meaningless. Consider what would have happened had Stonehenge or the Pyramids of Giza been dismantled and reused as building materials prior to their documentation in the historical record. What, if anything, would archaeologists have been able to deduce, even if we were aware that there was such a significant absence in the record? Documentation of archaeological sites, especially those that are threatened or faced with imminent destruction at human hands, is essential.

With the modifications to the equipment and methodology already in place for the ELRAP projects, our laser scanning contingent was already adapted towards rapid digital documentation which could be applied to nearby threatened sites or sites that needed to be quickly scanned for other reasons. During the 2011 field season of ELRAP, two such instances of Rescue Lidar were attempted, one to record a robber's pit at Khirbat Faynan and the other to preserve the threatened mining site of Umm al-Amad. In the midst of the 2012 field season of ELRAP, the opportunity arose to implement speed scanning at the famous Nabataean site of Petra. Each of these three case studies of 'Rescue LiDAR' will be discussed in brief below.

### *2.1a Case Study: Rescue LiDAR at the Robber's Pit and Cistern of Khirbat Faynan*

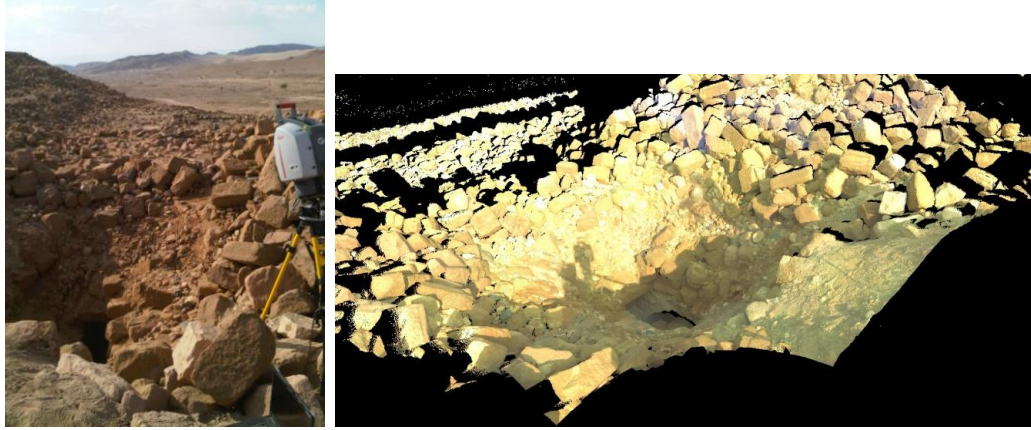
As argued above, one of the aims developing the 'Rescue LiDAR' methodology is to not only to digitally conserve archaeological sites, but also to answer questions that relate to problems linked to large archaeological theory. In the Faynan copper ore resource zone of southern, my theoretical interests focus on the nature of social control of the region during the Roman and Byzantine periods. Previous research has shown that the region was a key

economic resource exploited in the eastern Empire of Rome (Mattingly 2011) as well as the seat of a Bishopric during the Byzantine period (Najjar and Levy 2011). One of the major questions concerning the Roman period in this area concerns the nature of local elites and their political control of Faynan in the late Roman period (ca 3<sup>rd</sup>-5<sup>th</sup> c. BCE). As will be shown below, the accidental discovery of a 3<sup>rd</sup> c. CE villa on the slopes of Khirbat Faynan provides an interesting case study for examining aspects of the household who resided in the villa (Levy forthcoming). Rescue LiDAR provides a quick and accurate way to capture a diagnostically viable point cloud through which the exact volume of different architectural structures; in this case, a beautifully constructed cistern that served the residents of the villa, can be determined. Using water consumption data from ethnographic and archaeological research in the Negev desert (Evenari, et al. 1982), it would be possible to establish the relative size of the household linked to this monumental dwelling.

During the course of the LiDAR survey of the landscape around Khirbat Faynan, an extensive robber's trench was identified on the northern plateau off of the southwestern corner of a monumental religious complex believed to be the ruins of an Early Byzantine church ((Barker et al 2006, Barker et al 2007, Mattingly 2011). The trench encompasses a deep shaft which penetrates into a series of subterranean archways which open into a larger room beneath them. Given that the interior walls of the subterranean chamber featured decorated plasterwork, and a quantity of fine Byzantine glassware and human and animal remains; this vandalized space seemed to be of some palpable archaeological significance and was theorized to represent a cistern.

It remains unclear how long had passed since the trench was dug, however, the potential return of the looters was implicitly eminent, given both the recent foreign interest in the site and an upsurge of similar looting of archaeological venues nearby. It seemed likely

that more destruction would occur upon the departure of the archaeological team from the area.



Figures 7A and 7B: Figure 7A displays the Leica Scanstation 2 HDS 4050 positioned on the Tilt Head on the edges of the Robber's Pit at Khirbat Faynan. Figure 7B is a screenshot of the local point cloud encompassing the robber's pit (center). Images from the author.

In an effort to not arouse additional interest towards the excavation's keen attention to the trench, rescue excavation activities on the North side of the city of Khirbat Faynan were conducted during the Eid al-Adha festival when the majority of local workers were excused from work. Over a two day period, the robber's backfill was duly sorted and cataloged, interior panoramic and traditional photography conducted, and most importantly, the exterior and interior were laser scanned using the equipment modifications specified earlier. The shaft downwards would have been in significant laser shadow and perhaps not scannable without the Tilt Head. The interior would not have been within the bounds of scannability were it not for the new, smaller, Quadropod base. Even with the smaller base, there was great difficulty in lowering all of the equipment down into the pit and positioning it appropriately.

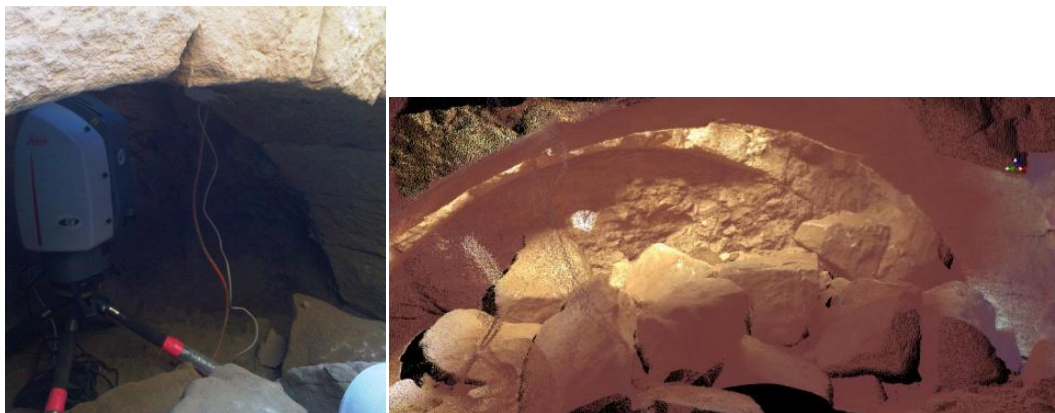


Figure 8A & 8B: Figure 8A is a photograph of the Leica Scanstation 2 HDS 4050 positioned on the Novoflex Quadropod inside the Robber's Pit. Figure 8B is screenshot of the point cloud of the interior of the Robber's Pit. Images from the author.

In all, two days in the field were spent on a rapid digital documentation of the robber's trench. Of these, the initial twelve hours of the first day were devoted to the high resolution scanning of the interior. Even with this seemingly significant chunk of time, however, some few laser shadows remain among the rocks littering the floor of the pit, and one small area at the top of the shaft whose line of sight is not appreciable from any safe vantage point either above, on surface level, or below, from within the pit. The laser scanning inside the pit was conducted while the sieving of the backfill occurred above, further speeding up the process.

In all, six high definition scans at varying resolutions and ranges were collected; representing a cloud of twenty-two million points. The point cloud of the pit and its surrounding surface area were stitched together during a single work day of registration (approximately eight hours). The speed of registration and high accuracy of the stitching, despite the lack of official targets were aided by the detail on the stonework of the architecture. The resulting point cloud has since been added to the larger five billion point cloud of the landscape of Khirbat Faynan. As a record of transient destruction, the robber's

pit section of the cloud provides an insightful look into the politics of looting in the Middle East, and the fragility of publicly known archaeological sites.

Further excavation was conducted in and around the robber's trench during the 2012 season and additional scans were taken of the pit fully excavated, revealing it to be a finely wrought cistern. Proximal excavations to its southwest revealed several rooms believed by the excavation team to be an elite residence, presumably dating to the late Roman period (dating forthcoming). Comparable figures from the two sets of point cloud models created of the pit cum cistern would reveal an approximate (the 2011 point cloud of the cistern looted, but unexcavated) and actual volume (the 2012 point cloud of the cistern looted and excavated). Local archaeological and ethnographic data projects that a cistern of this volume and quality of construction could effectively provide water for a household population of (Evenari 1982). Calculating out the volume of a space within a point cloud is not an easy matter. Beyond the typical post-processing and registration of the associated scans, this can be accomplished via two different, both equally time consuming and painstaking ways. Either the point cloud can be converted to a mesh, exported away from the proprietary software (Cyclone) and into something like Meshlab, a 3D polygon created around it to encase the radical atoms of the space, and the percentage of point cloud to empty model space calculated, and then reapplied to the mathematical scale one can derive from orthographic photographs of the same space which contain a knowable scale. Or the point cloud can be painstakingly sliced at minute known intervals to create a 2D plane, whose aggregate areas could be converted into the volume of the space. It is a doable, but time-consuming and therefore ineffective methodology. However, now that such a quantitative need has been identified, solutions can be built into the in-progress software for point cloud



visualization which would efficiently and effectively complete comparable algorithms to retrieve such anthropologically useful data.

It should further be noted, that though the 2012 excavation provided further opportunities to analyze the space and provided additional contextual data to support the cistern hypothesis- even had the space been destroyed or further looting through the interior walls occurred- the original model collected via Rescue LiDAR would have been capable of providing the diagnostic evidence to conclude its potential function as an elite cistern and hint at the number of people who would have been capable of accessing its limited resources.

#### *2.1b Case Study: Rescue LiDAR at Umm al-Amad, A Roman Copper Mine*

The second case study is also directed at the Roman period in southern Jordan and likewise utilizes a volumetric diagnostic analysis of point clouds measured via point cloud models. Case study two focuses on one of largest Roman mining complexes known from the empire (Mattingly 2011; Oleson 2008). Nelson Glueck (1940) first discovered this Roman mine in the 1930s, very cursory studies were carried out by the Deutches Berbau Museum (Hauptmann 2007) and the British CBRL (Mattingly 2011) However, none of these passing research teams were able to map this massive mining complex until we applied the Rescue LiDAR system described above. Today, the mine is stripped of its ore, removed during the Roman period. The social question that is addressed here concerns the amount of ore that may have been retrieved from Umm al-Amad. By estimating the quantity of ore mined, it is possible to estimate how much copper metal was produced. This estimate is an indication of how much copper was available for the production of artifacts and further trade (of both artifacts and raw metal) and can pinpoint the economic prosperity of this remote Roman outpost.

The Wadi Faynan region and the surrounding Sharra Mountains are rich in copper ore deposits which contributed significantly to the area's role as a major ancient center of metallurgical production (Mattingly 2011). Recent mining interests have re-focused on the region, threatening much of the rich archaeological palimpsest. Even with no concrete mining works in place, new roads through the mountains for potential mining projects have begun to threaten the stability of isolated mountain sites. Over the course of the 2011 Field season, rumors regarding the state of the Roman copper mine of Umm al-Amad came to the attention of the ELRAP staff. Though fleetingly surveyed at least twice over the past one hundred years no detailed documentation of this site existed, despite its role in the Christian massacre at Phainon (Glueck 1940, Mattingly 2011, Najjar and Levy 2011).

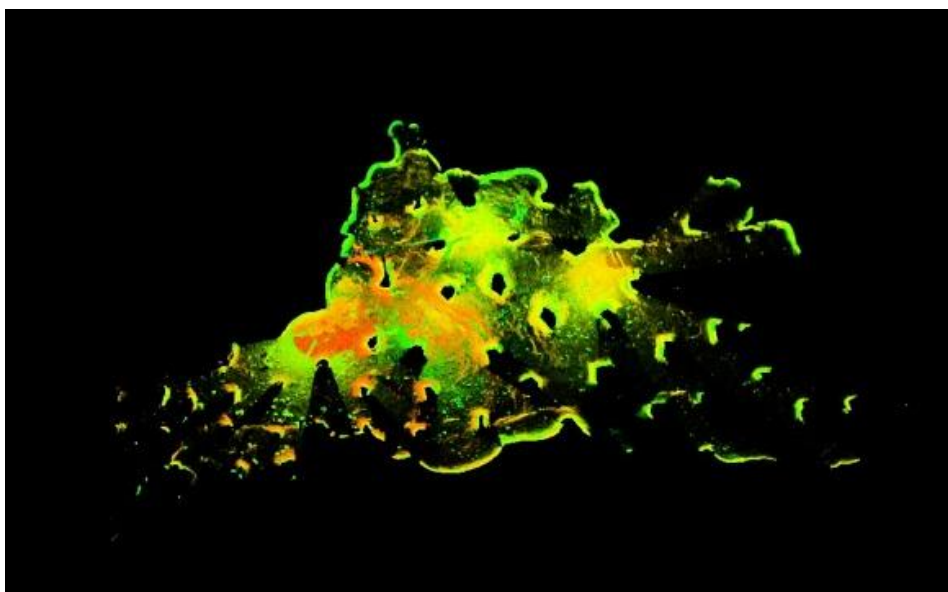


Figure 9: Screenshot of a faux 'aerial' view of Umm al-Amad's interior layout. *Approximately 80 meters of its speculatively 150 meter depth were captured during our eight hours of scanning to create this point cloud.* As the only digital record of the site, the capacity of terrestrial LiDAR to create such a map is revolutionary.

Given the success of the rescue LiDAR mini-project at Khirbat Faynan, and specifically, our now proven ability to scan interior, tight places- a day long expedition to scan the threatened site of Umm al-Amad was planned with less than two days notice and little information beforehand on what to expect from such a site.

Located in a remote mountain valley, Umm al-Amad ('the Mother of Pillars') is a one hundred and fifty meter horizontal gallery of carved columns running back into the peak from a series of low cave entrances. Recent construction had already caused a back area to collapse, and even while we worked at the site the vibrations of distant dynamiting for road construction could be felt through the stone. The entry is situated in a steep cliff face reached by a narrow precipitous pathway. The mine is entered through one of several carved archways, which are blocked up with sediment and goat excrement, so that entry must be obtained via crawling, with the scanning equipment dragged carefully in behind. Approximately twenty meters into the mine the height of the man-made cavern increases to approximately two meters, allowing for standing. No lighting was available to bring along on the rescue expedition and thus the point cloud's photogrammetry is the result of later editing in Visicore.

Eight and a half hours were spent at Umm al-Amad, which resulted in eight scans at a variety of resolutions and ranges, utilizing black and white paper targets taped to the columns where and whenever possible. The resulting point cloud was by no means representative of the entirety of the mine galleries. But this twenty five million point cloud was a significant portion of the site, one which we could not have documented as accurately or as quickly via any other method. Despite the partial nature of the data, its registration was far more intensive than the Khirbat Faynan robber's pit and entailed several days of versions of its registrations before a satisfactory constraint error margin was attained.

As with the Roman cistern, a volume could conceivably be calculated out from the mines. Though given the complexity of shape (as compared to the purposefully constructed polygonal looter's pit of the previous example), it would have to be calculated out from a mesh conversion or through the new in-built volumetric generator that will be part of the in-house CISA3 software, Visicore. The volume of the mine could conceivably be used, with reference to previously collected statistics (Hauptman 2007), the volume of ore extracted from this type of geology. The volume of ore could be utilized to hypothesize the amount of metal producible, giving a gage for the economic capability of the mine and those who controlled its resources.

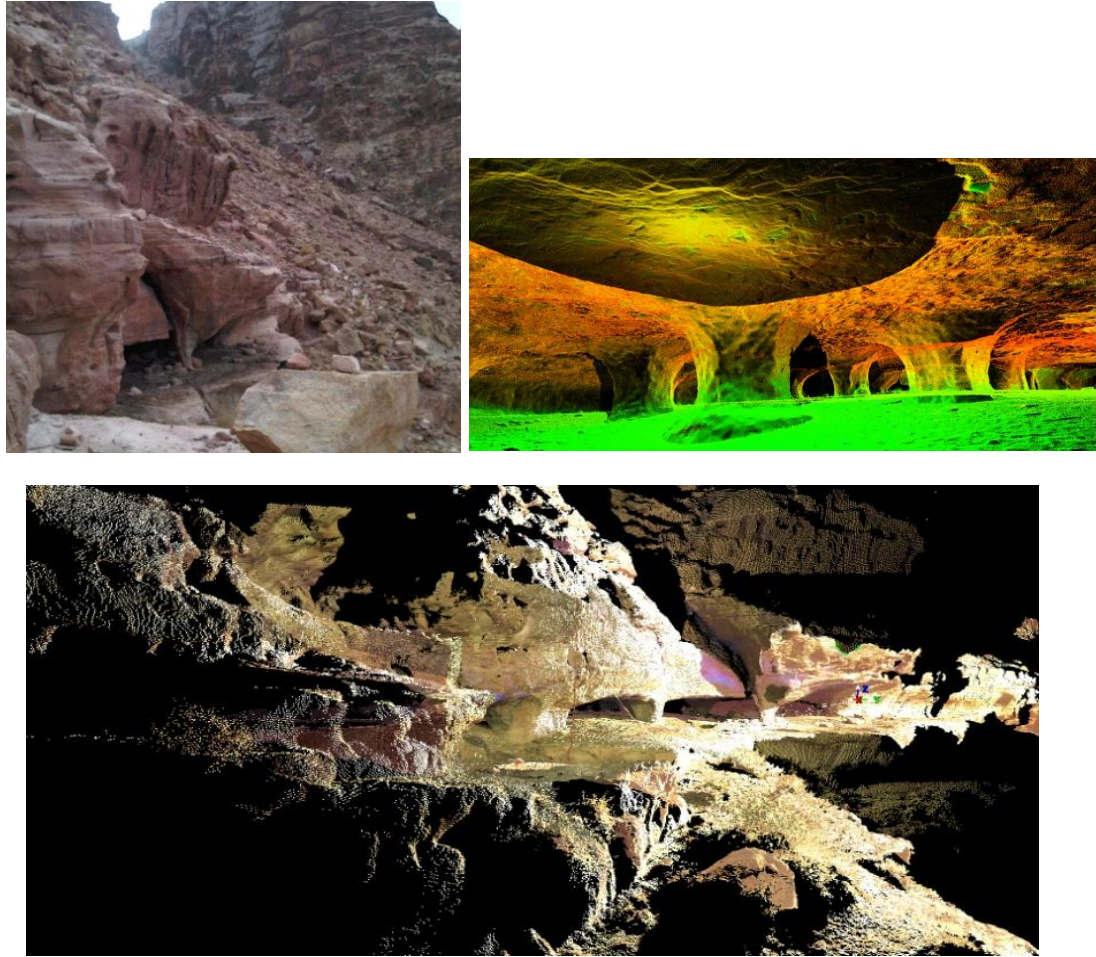


Figure 10A, 10B, & 10C: From top left, clockwise. Figure 10A is a photograph of the exterior entrance into the canyon, as compared to the screenshot of the point cloud of the same space in Figure 10C at the bottom. Figure 10B is a screenshot of the point cloud of the interior of the mine, without additional photogrammetric coloring. Images from the author.

### 2.1c. Case Study: Speed Scanning at Petra's The Temple of the Winged Lions and the Petra Byzantine Church

Having described two applications of Resue LiDAR as a tool for helping to solve social archaeological questions above, here the method is applied as a tool to create further diagnostic content for conservation. Utilizing the data collected quickly in the field, an analytical map of the site and, specifically its finely detailed mosaics can be created to aid in

conservation practices. As part of the 2012 season of ELRAP, certain contingents of the field school were asked to participate on a brief project at Petra in conjunction with the American Center of Oriental Research's Temple of the Winged Lion Project. The brief terrestrial laser scanning (LiDAR) digital documentation survey of Petra collected three point clouds of the interior of the Byzantine Mosaic Church, representing approximately ten million points; and five point clouds of the Temple of the Winged Lion, totaling approximately twenty-eight million points. The survey was conducted over a single day utilizing a Leica ScanStation 2 in conjunction with the rapid scanning or 'Rescue LiDAR' methodologies concocted by UCSD's ELRAP over the past seasons of using LiDAR in the field. The Petra church was scanned rapidly in the morning while the Temple of the Winged Lion underwent balloon photography. Its ten million points encompass its interior architecture as well as high resolution detail on the north and south mosaic aisles, particularly their west ends. The Temple of the Winged Lion was scanned throughout the afternoon, resulting in the collection of data points for its interior and exterior architecture, as well as much of the exterior craft areas surrounding it. Scanning additionally





Figure 11: A screenshot of the interior of the Petra Mosaic Church, as shown in Visicore.

acquired a point cloud of the façade of the Great Temple across the way. Simultaneous with the laser scanning, a photogrammetric survey was undertaken by CISA3 colleagues Vid Petrovic and David Vanoni of the two areas to collect photographs suitable for the creation of point clouds via the Structure for Motion techniques being experimented with at UCSD's CalIT2 CISA3 and the CISA3 Augmented Reality program ARtifact of Mr. Vanoni. Over eight thousand images were collected by the photography team to be used in the creation of a Structure for Motion point cloud of each site. This entailed the documentation of each feature of the site from a systematic variety of angles at a comparable photo exposure. These sparser point clouds will be utilized to enhance the high resolution point clouds collected from LiDAR by filling in laser shadows left by the mechanism. Additionally, the high quality imagery collected as part of the Structure for Motion survey will be utilized to enrich the photo-realism of the LiDAR dataset as part of the enhanced visualization projects

conducted by UCSD's CalIT2 CISA3 for digital diagnostic and tourism viewing (Rodriguez-Gonzalez et al 2011; Shaw and Corns 2008). The LiDAR point clouds will be further used as recognition reference points for ARTifact.

In a single day the speed scanning methodologies of Rescue LiDAR were able to capture strong point clouds of two infamous cultural heritage monuments, as well as a glimpse of a distant third. Bear in mind also, that the ScanStation2, as an ancient though sturdy model of scanner, is one of the slower models of scanner to begin with. And that if a newer, faster model was used in combination with the techniques under discussion-even further levels of data might have been collected from Petra that day.

Had the ELRAP project not had the modified equipment to tackle the first two rescue projects discussed above, there is a very high potential that aspects of the first two sites would be lost to posterity. Flexible digital documentation in the field utilizing laser scanning allowed these areas to be preserved for future analysis. Without the speed scanning capability harnessed for ELRAP, CISA3, etc, only part of one of the sites at Petra would have been documented on our singular day of field work there.

The successful implementation of 'Rescue LiDAR' in these ELRAP projects demonstrates how laser scanning can be utilized not simply for documenting primary excavation sites and ancient monuments, but to capture time-sensitive projects. With this capability we can collect crucial vanishing cultural heritage data on threatened sites in the form of digital point clouds for further analyses and 3D presentation without causing significant political delay between nations during armed occupation (Green 2010, 111), with corporations on tight construction schedules, or when local antiquities authorities are only wishing to issue limited time permits for archaeological work. These projects are apt



examples of the intersection of archaeology and technology that is the heart of the interdisciplinary research which is the future of archaeology and cultural heritage preservation.

## 2.2 Temporal Scanning

Archaeology not only encompasses the study of natural deconstruction processes, archaeology itself is inherently a destructive process. Terrestrial LiDAR has previously been used to track the erosion process of the monuments and, now, per the work by the author on the 2011 ELRAP field season, the final excavation. But what about the excavation process itself? Is this record of destruction, of sudden man-made erosion, not of interest, particularly to generations of subsequent archaeologists who could not be present at the excavation itself? Given the new speed with which terrestrial LiDAR can be deployed, if it can be worked into the excavation schedule to scan this process, it might therefore contribute towards both the study of the deconstruction process of the site and of the archaeological investigation conducted upon it.

Previous experiments have been conducted towards tracking erosion processes on rock-faces (Barett et al 2005; Olsen 2009; Wasklewicz et al 2004) and mud-brick (Barton 2009), and therefore temporal data of a certain nature has previously been collected. However, as little relevant work has been completed addressing the build-up of lighter sediments on sites to investigate the laser scanner's capabilities in tracking minute changes in sedimentation and its stratigraphy. The preservation of the excavation process would create a highly detailed record of the site destruction process, the likes of which has never yet been undertaken. If the scanning of the full on-going archaeological excavation process is to be attempted in upcoming field seasons, it is necessary to explore the appropriateness of scanning tiny alterations to sediment layers to determine at which point and how often

scanning of stratigraphic differences should be undertaken in the field to create a series of useful time-lapsed point clouds without wasting significant field time, giving the scanner's resolution limitations and dependence on photogrammetric elements after its minimal resolution is met.

Furthermore, the issue of how to meaningfully manage and visualize multiple concurrent point clouds of similar spaces, needed to be addressed in order to handle the incoming point cloud data sets from future field work. What is the best way to archive and visually track a series of point clouds of the same thing with only minute changes using existing software-or does something new need to be developed, perhaps in Visicore?

#### 2.2a Case Study#4: Sediment Intervals and Site De-Formation Processes: Exploring Time Lapse Laser Scanning Capabilities and Methodologies for Archaeology or Sand Castles for Science (SCS)

To investigate the potential of temporal scanning for field archaeology, a National Science Foundation funded mini-grant project entitled Sediment Intervals and Site De-Formation Processes: Exploring Time Lapse Laser Scanning Capabilities and Methodologies for Archaeology was commissioned by CISA3 and managed by the author. Beach sand was decided upon as the most relevant medium for investigating the scanner's capacity for visualizing sediment layers. Sand is a fast moving particle grain which can be easily manipulated and which is found in abundance along the California coast. Given the desert ecology of ELRAP's test sites in Jordan, it was furthermore deemed a solid comparable for certain local soils that would be encountered in the field (Bagnold 1940; Drucker 1972; Welland 2009). Under the auspices of the project, several variations of sand manipulation

were scanned, most infamously among them sandcastles, leading to the project's name as a public outreach initiative as Sandcastles for Science and therefore its acronym, SCS.

In all instances of sand manipulation, baseline scans of the as-is area cordoned off for the experiment were scanned. The sand was then manipulated into a different position via raking, footprints across it, or basic sandcastles; and then scanned again. Each of the experimental point clouds would then be compared to its preceding control scan in an effort to determine what the smallest rate of measurable change in particle movement was between scans and which is visible in the point cloud and its photogrammetric elements. Such comparatives will be made by measuring digital elevation models (DEMs) and finer slides created from the resultant point cloud data against each other to mathematically account for change.

The comparative data from the raked and walked upon scans indicated that the terrestrial laser scanner was capable of tracking this level of movement from the baseline scans. This is what was anticipated, but needed to be established as a firm control for looking at ever smaller areas of detail. In the more interesting case of the sandcastle construction, a third level of scanning was conducted after the sandcastles were further decorated using small implements like dental picks. This created a fine level of detailing which would prove to be a significant challenge to the scanner's (again the Leica ScanStation2) minimum resolution of one millimeter by one millimeter. To help further gage the visualization aspect of the project, a fourth series of scans was taken of the sandcastles mid-destruction.



Figure 12: The Leica Scanstation 2 poised to begin the third round of scanning at Torrey Pines Beach.

SCS created an efficient temporal scanning workflow and provided visualization practice towards transitioning simultaneous digital space. But, ultimately SCS ultimately proved that the scanner alone would only be capable of collecting visible data on large sedimentation shifts and of general stratigraphic layers on sections in side bulks. It would therefore not be worthwhile to scan minute changes in soil without additional technical aid from other resources. The data collected on the mosaic tesserae from the Petra Mosaic Church during the 2012 season reinforced this notion. The small tesserae are clearly and distinctly visible, but could benefit from a higher resolution of detail which laser scanning alone cannot provide. SCS in conjunction with the tesserae corroboration has prompted the on-going creation of several upcoming research projects into combined technologies which

may provide a streamlined solution towards capturing further pockets of supra-high resolution data amidst the already high resolution point clouds being captured in landscape scanning situations. This may be particularly useful in point cloud visualization of stratigraphy. Like the Petra tesserae, stratigraphy is visible in the point cloud, but would be of more significant diagnostic interest if at a higher resolution, as this would provide an unbiased multi-perspective viewable representation of the space, alleviating some of the bias concerns in documenting stratigraphy (Warburton 2003:29-30). A comparative between the visualization of stratigraphy via point cloud, traditional illustration, and orthographic photography is something currently being developed by the author.

#### 2.2b Case Study #5: Khirbat Faynan Area 18

Following the knowledge gained from SCS, i.e. that constant scanning of minute changes to the excavation would not be worthwhile- one to two day intervals between scanning was decided upon as a reasonable experimental first go at the applied concept. Even then, this interval was hard to keep to given the grueling field schedule of excavation. Given the expected architectural finds, the excavation of Area 18 at Khirbat Faynan was selected as the best case study to attempt temporal scanning of the archaeological excavation process. Area 18 includes the robber's trench discussed earlier, but focuses primarily on a small section just to the west of the looted area. Six sets of conglomerate point clouds were collected, representing six different stages in the area's destruction via archaeology.

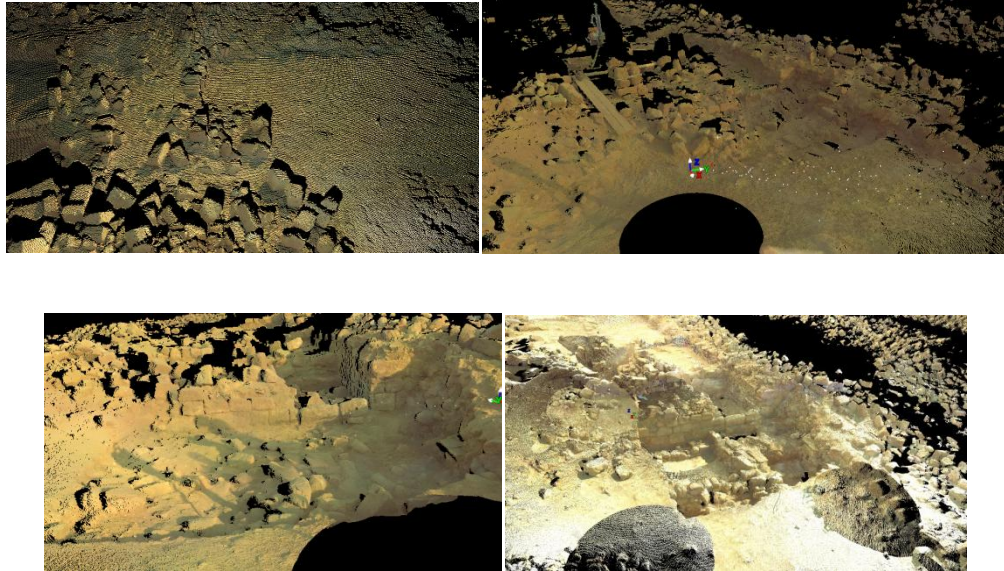


Figure 13A, 13B, 13C, and 13D: Clockwise from top left. Figures 13A through 13C are screenshots raw point clouds from the temporal sequence displaying the archaeological excavation of Area 18 at Khirbat Faynan. Figure 13D is a screenshot of the conglomerate point cloud at the end of excavation which will go on to be utilized as the archaeological data framework for annotation and dissemination.

Where once upon a time the record of a site's excavation consisted solely of the notes of its archaeologists, we have moved into a marvelous digital age. First singular points of geospatial data were collectable. And now vast clouds of points can be brought back from the field to virtually represent not just the finished excavation, but the excavation process.

Chapter 2.1 and Case Studies 2.1a and 2.1b, in part, are an abbreviated version of the material as it appears in Richter, A.M., Kuester, F., Najjar, M., and Levy, T.E., 2012. *Terrestrial Laser Scanning (LiDAR) as a Means of Digital Documentation in Rescue Archaeology: Two Examples from the Faynan of Jordan*. Proceedings of the 18th *IEEE Virtual Systems and MultiMedia (VSMM)*, Milan 2012. The thesis author was the primary investigator and author of this paper.

## CONCLUSION

This thesis has illustrated that terrestrial laser scanning can be used towards the scanning of large archaeological landscapes, effectively putting the archaeological site into its environmental context. The limitations of the scanning mechanism can be overcome to make it an efficient tool for such archaeological purposes. Furthermore, now that laser scanning can be an expedited process, it can be used to help preserve endangered archaeological sites and document the archaeological excavation process. The point clouds created from efforts such as those described above can be utilized not just as archival quality digital documentation (Warden 2007), but as a framework for interpreting archaeological data and disseminating the history represented within the point cloud to others. Terrestrial LiDAR makes the archaeological site itself an artifact that can be taken home with the archaeologist for further investigation, measurement, and analysis.

Terrestrial LiDAR is a way of explaining the past—a visually stunning and captivating way of illustrating history which people will hopefully pay attention to. The immersive environment point clouds offer a 3D viewer provide deeper inroads into archaeological use of digital experiences, whereby people can experience sites and archaeology in these virtual worlds without having to travel there themselves. This opens up a whole new realm of physically palpable armchair archaeology to the public. It provides a new means of analytical publication for archaeologists—possibly saving future sites from languishing in the unpublished state many are doomed to (Hammer 2000:143).

This thesis has been primarily technical in nature and has, admittedly favored aspects of information science technology or archaeo-informatics (Llobena 2011) far more than anthropological archaeology. As the beginning steps forward towards embracing this

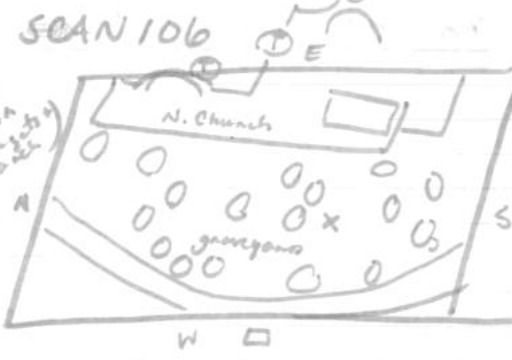
new technology into the archaeological tool kit, this has been a necessary diversion in applied archaeological science rather than a humanitarian quest. In order to provide an archaeological landscape to study the cognitive use of space in the ancient world and ecological perspective, an archaeological landscape must first be obtainable. Remote sensing spatial visualization technologies like terrestrial LiDAR and its point clouds provide the bridge between science and theory, creating an interdisciplinary solution to begin applying hermeneutic approaches. It is a melding of technical application and the humanities (Llobena 2000:121). And it is a solid reflection of the interdisciplinary work at CISA3-which bonds together empiricism of computer science and engineering with the warmer humanistic focus and direction of archaeology. It is part of the new world order of interdisciplinary efforts which should be at the heart of the goals of modern discipline of archaeology (Crumley 2006:389).



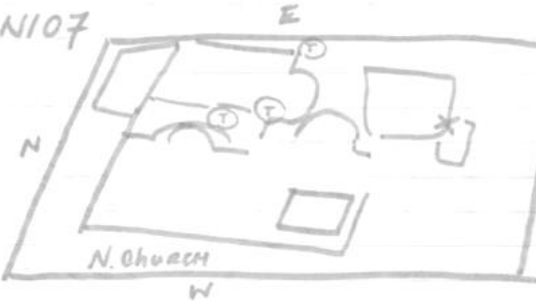
APPENDIX

Sample of the worksheet developed for metadata collection.


Day 26 Station 1 SCAN106  
11/09/11  
I: 6:23 - 6:28  
S: 6:30 - 7:07 (at peak of high sun on the side)  
Res: 1cm x 1cm @ 8 m  
Exp: 250  
#: 5027 x 708  
image pre-sun on high exp → white noise  
shots/glare on it ☺



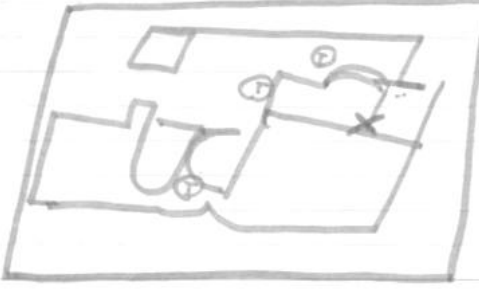
Day 26 Station 2 SCAN107  
11/09/11  
I: 7:30 - 7:35  
S: 7:36 - 8:23  
Res: 1cm x 1cm @ 8 m  
Exp: 55  
#: 6283 x 935



Day 26 Station 3 SCAN108  
11/09/11  
I: 9: - 9:38  
S: 9:42 -  
Res: 1cm x 1cm @ 12  
Exp: 45  
#: 7,540 x 1,406



Day 26 Station 4 SCAN109  
11/09/11  
I: 11:07 - 11:10/12  
S: 11:13  
Res: 1cm x 1cm @ 10 m  
Exp: 45  
#: 6,283 x 999



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