Three-Dimensional Epigraphic Recording at Stobi (Former Yugoslav Republic of Macedonia): Creating a Virtual Lapidarium

M.A. Major Research Paper

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ABSTRACT

There is an increased need for 3D recording of archaeological sites and digital preservation of their artifacts. Digital photogrammetry with prosumer DSLR cameras is a suitable tool for recording epigraphy in particular, as it allows for the recording of inscribed surfaces with very high accuracy, often better than 2 mm and with only a short time spent in the field. When photogrammetry is fused with other computational photography techniques like panoramic tours and Reflectance Transformation Imaging, a workflow exists to rival traditional LiDAR-based methods. The difficulty however, arises in the presentation of 3D data. It requires an enormous amount of storage and end-user sophistication. The proposed solution is to use game-engine technology and high definition virtual tours to provide not only scholars, but also the general public with an uncomplicated interface to interact with the detailed 3D epigraphic data. The site of Stobi, located near Gradsko, in the Former Yugoslav Republic of Macedonia (FYROM) was used as a case study to demonstrate the effectiveness of RTI, photogrammetry and virtual tour imaging working in combination. A selection of nine sets of inscriptions from the archaeological site were chosen to demonstrate the range of application for the techniques. The chosen marble, sandstone and breccia inscriptions are representative of the varying levels of deterioration and degradation of the epigraphy at Stobi, in which both their rates of decay and resulting legibility is varied. This selection includes those which are treated and untreated stones as well as those in situ and those in storage. The selection consists of both Latin and Greek inscriptions with content ranging from temple dedication inscriptions to statue dedications. This combination of 3D modeling techniques presents a cost and time efficient solution to both
increase the legibility of severely damaged stones and to digitally preserve the current state of the inscriptions.

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1. Introduction

How archaeological sites are recorded is changing rapidly as a result of more readily-available digital recording techniques. The first digital recording practice adopted by archaeologists was that of digital photography, a natural progression from film photography that was a commonplace tool amongst archaeologists. The modern archaeologist utilizes a growing array of digital recording tools such as LiDAR, GIS, Structured Light Scanning, Multi-Spectral Reflectography amongst others. The merit of many of these digital techniques for recording and preserving data in archaeological settings is often outweighed by their prohibitive cost. The modern prosumer digital single lens reflex (DSLR) camera is an inexpensive tool that is arguably one of the most valuable tools for modern archaeologists in that can provide digital recording technology to practitioners on a budget. The rise in popularity and decrease in cost of the DSLR camera has driven the development of the proposed techniques for digital preservation and focus on the DSLR as the primary tool for capturing data in the field. The DSLR camera can be utilized without much expense or modification for digital photogrammetry, Reflectance Transformation Imaging (RTI) and HDR 360° Virtual Tours.

Presently the need for 3D digital recording of archaeological artifacts and sites is growing in demand; this is part of the emerging trend of what is being called Virtual Archaeology or Virtual Heritage (Wessels, 2014). In Alonzo Addison’s words, he shares the commonly held

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sentiment that the “first wave of VR worlds failed to live up to the promise.” The let down of first-wave virtual worlds of the 1990’s and early 2000’s was due to the fact that they offered low resolution, unrealistic visualizations, and limited options for analysis in the VR environment. Moreover there was no concern for long term digital preservation, due to the lack of consistency in file formats between researchers digitizing collections and a general apathy for long term preservation. Early VR suffered from excessive enthusiasm, questionable accuracy and often times would be out performed by a basic 2D photography. This can mainly be attributed to the lack of sufficient processing hardware but more significantly most of the early VR worlds and models were left to the creative mind of the artist rather than a strictly objective data recording methodology.

The lack of suitable 3D data collection and representation persuaded the archaeological community to remain with the previously accustomed method of recording 3D data in two dimensions. Yet attempting to record 3-dimensional elements of the real world in only 2-dimensions not only leads to misrepresentation but also to inconsistencies and inaccuracies. Hand drawings or basic 2D photographs cannot come close to capturing the realism and almost microscopic detail that modern 3D methods can easily achieve. Even the most skilled artist or draftsman cannot capture the three-dimensional form of an object or building without painstakingly producing a physical model which even then can never achieve the same level of accuracy as digital methods. In his article on photogrammetry for underwater archaeology, Van

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Damme further explains the detriments of only having 2D recording in that most techniques - with the exception of photography - are not very accurate, quite time consuming and prone to human error. They most importantly fail to capture all the complexities of three dimensional data which is an integral part of archaeological sites and interpretation.\textsuperscript{5}

The re-emergence of new VR worlds and techniques in the heritage community can be credited to the fact that detailed 3D data of actual sites and finds can now be inexpensively captured and produced for archaeology without the need of an artist's interpretation. With the emerging digital techniques such as photogrammetry, LiDAR, RTI, multi-spectral photography, virtual tours, among numerous other experimental techniques, becoming more available, there are new methodologies being explored based on their implementation in academic archaeological situations. This is expressed in the three domains of second-wave Virtual Heritage: 3D documentation, which includes site surveys and epigraphy; 3D representation, which includes virtual anastylosis and visualizations; and 3D dissemination, which includes immersive networked worlds and \textit{in situ} augmented reality.\textsuperscript{6}

There are six main target user groups of Virtual Heritage content, which are classified as follows by Wessels:

“(1) archaeologists and historians who are interested in understanding the past, (2) museums and on-site interpretation centres, which the public visits to experience and learn from, (3) schools and education professionals, (4) experimenters who are individual testers or students, (5) the entertainment industry which includes computer games and the media ... [and] (6) conservators and restoration experts.”\textsuperscript{7}

\textsuperscript{6} Addison,"Emerging trends in virtual heritage.", 22.
\textsuperscript{7} Stephen Wessels, Heinz Ruther, Roshan Bhurtha, and Ralph Schroeder. "Design and creation of a 3D Virtual Tour of the world heritage site of Petra, Jordan". Proceedings of AfricaGeo, 1-3 July 2014 (2014); As a result Wolfenstetter offers the additional point that AR technology allows museums to bring awareness to cultural heritage and attract
Digital photogrammetry as such is a suitable tool for 3D documentation of epigraphy in particular, as it allows for the recording of inscribed surfaces with very high accuracy, often better than 2mm and with only a short time spent in the field.\(^8\) With the produced models later enhancements can be made with specialized, but often with free 3D manipulation software. RTI can further enhance the detail of faint epigraphical inscriptions that cannot be captured through photogrammetry alone. These techniques are completely non-destructive unlike other epigraphical recording and preserving techniques such as inscription squeezes. In this process a special moisturized paper is placed on top of the inscription and rubbed with a specifically designed brush. After the lettering appears on the paper it is left to dry and serve as a record of the inscription.\(^9\) At times other materials have been used such as latex or liquid rubber. In all cases with the squeeze technique contact with the inscription must be made and in the removal of the squeeze portions of the inscription can be removed with it. In the case of digital photogrammetry no physical contact is required with the objects in study and therefore there is no risk to damage or hinder the preservation of them. In addition, photogrammetry and RTI record all available data without any incorporation of wishful thinking, unlike older publications that relied on an individual's interpretation of the data that had to be represented in a sketch.

Digital photogrammetry and RTI have traditionally remained independent recording techniques, but they should be viewed as complementary techniques as they can be combined to

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produce a multi-layered enhanced version of the original. Photogrammetry and RTI in combination are currently one of the best ways to accurately publish an object, virtually preserve it and digitally enhance it to reveal hidden information. The list of uses for 3D Virtual Archaeology range from historical documentation, digital preservation and conservation, timeline comparisons, degradation and deterioration monitoring, 3D archives, web-based geographic information systems, virtual anystylosis, and multimedia museum exhibitions.\(^{10}\)

After the collection of high quality 3D recordings difficulty arises in the presentation and dissemination of the 3D data. Although offering more detail, accuracy and immersion than a simple 2D drawing, in a publication 3D data has previously required skilled technicians as well as expensive software and hardware to manipulate and study. Fabio Remondino highlights the fact that 3D data “is often subsampled or reduced to a 2D drawing due to a lack of software or knowledge in properly handling 3D data by a non-expert.”\(^{11}\)

The proposed solution is to use game engine technology and high definition virtual tours to achieve the goal of providing scholars and the general public with an uncomplicated interface to interact with the detailed 3D epigraphic data. With these tools the complicated 3D data can be interacted with and studied from the internet through a web-browser. In the web-browser application there is no need for the user to have advanced graphics cards, large amounts of local storage, or access to expensive software because all of the data is held remotely in secure servers. There are no longer limitations of slow dial-up internet connections and with modern data transfer speeds the ability to have impressive 3D results in an online setting is possible. This solution based out of a web-browser not only allows for epigraphy to be viewed in 3D but also


\(^{11}\) Remondino, "Heritage recording and 3D modeling with photogrammetry and 3D scanning." : 1104-1138.
measured, re-lighted and manipulated which are actions that are often impossible to perform in the field because objects are in storage, in hidden areas or inaccessible by the public.\textsuperscript{12} In addition, certain notable features of these objects that could be missed at first glance can be highlighted and annotated directly on the object. Using a selection of inscriptions from Stobi in the FYROM as a case study this paper will demonstrate the viability and performance of these techniques and methodology for other Classical sites and museums.

As an additional benefit, the proposed 3D models and Virtual Tour will drive public interest and tourism due to their welcoming interactivity. In the case of Stobi in particular, this is an invaluable asset due to the fact that one of the primary sources of the site’s funding is tourism. As Erik Champion says “in a virtual environment then, the setting should also be an interactive artifact, you should be able to interact with the environments as much as a local,” and this is because people learn best through active engagement and interaction.\textsuperscript{13}

\section*{2. The current state of Stobi’s Epigraphy}

Stobi is located roughly 600 kilometers north of Athens and 70 kilometers south of Skopje, FYROM’s capital city. It existed first as a city under the Romans in the 2nd century BCE and later becoming the capital of \textit{Macedonia Secunda} in the 5th century CE. The site’s historical significance is derived from its constant growth through the late Republic and early Roman Imperial periods where it had become a wealthy municipium. Excavations of the site first began in the 1920s and subsequent excavations have uncovered many important buildings,

\begin{thebibliography}{13}
\end{thebibliography}
notably including a large amphitheatre, the Episcopal Basilica and recently a temple dedicated to Isis with a preserved interior chamber [Figure 1]. The site is noted for its many and well preserved mosaic floors and extensive epigraphic collection.\textsuperscript{14}

A distinguishing aspect of Stobi is that it is the only known \textit{municipium} outside of Italy that had the \textit{ius Italium} status where they were entirely exempt from certain taxes, including the \textit{tributum soli} which was the land tax.\textsuperscript{15} There are only a few direct references to Stobi in ancient literature, mostly from Livy who refers to Stobi as a town of Paeonia and discusses the dealings of the military in the region in 197 BCE. Because of the limited information found in literature about Stobi, it is necessary to turn to the epigraphic evidence from the region to fill out the social and economic history of Stobi. Stobi’s epigraphy has helped to establish a chronology of the successive phases of habitation and provided insights into the art, culture, social infrastructure, economics and the environment in the city.\textsuperscript{16}

In 2008 the National Institution for Management of the Archaeological Site of Stobi was established, marking a new phase in excavation, research and scientific presentation for the site. The increased interest in the site makes it an ideal candidate to serve as a test case to determining the viability of emerging digital techniques into a virtual lapidarium. Of Stobi’s three hundred and nine inscriptions, a set of nine were chosen for digitization and recording to demonstrate the utility of digital photogrammetry, depth mapping, RTI, 360\textdegree virtual tours and game engine

technology for epigraphic display.\textsuperscript{17} This project is further served by the 2012 publication that collects and re-edits all of the epigraphical finds at Stobi and hence serves as a key reference in this project.\textsuperscript{18}

These inscriptions were selected as a subset to demonstrate the various advantages and disadvantages of new digital recording technology. This study was not intended to be a completely comprehensive digital recording of all of Stobi’s epigraphy. These test cases were comprised of: heavily damaged inscriptions - to determine the extent that the techniques could reproduce a legible equivalent, cases where the materials were known to be especially susceptible to weathering and a highly detailed record needed to be created, cases in which the goal was to simply improve the current photographic record that is published with these inscriptions and finally broken or fragmented monuments - to digitally reconstruct them in a virtual world.

Stobi’s inscriptions are comprised of sandstone, breccia, and marble and most of the epigraphs are exposed to the elements resulting in a constant state of weathering. The sandstone inscriptions are deteriorating at a much faster rate than any other stones with significant increasing damage reflected in their state on an annual basis. Exact weathering rates are not known and are dependent on the situational environmental factors of the resting areas of the stones. It has been recorded that in other areas depending on environmental factors marble inscriptions can deteriorate at a rate averaging from 0.1 - 3.6 mm/100 years and for sandstone 0.5 - 2.5 mm/100 years.\textsuperscript{19} Some conservation has been done of the inscriptions that were removed

\textsuperscript{17} See Figures 4 - 15.
\textsuperscript{18} I. Stob
from the field and now are in secure storage, however some of the inscriptions were left ‘in situ’ and cannot be removed and consequently are deteriorating at a faster rate due to being constantly exposed to weathering.\textsuperscript{20}

As early as 2004 when discussing the utility of 3D Virtual Reality technology for cultural heritage it was understood that in an exhibition space, funds to properly exhibit entire museum collections or archaeological finds is quite limited and would often prohibit otherwise valuable information from artefacts to be kept locked away unable to be studied. This is only worsened by the delicate nature and fragility of some objects that completely prevent institutions from displaying to the public. Even with those objects that are on display in a museum the interaction of museum visitors with the artefacts is completely curated and limited so that they cannot look at the objects from all angles, do any direct comparisons or hands-on study.\textsuperscript{21} These hindrances are overcome by the display of artefacts in a VR world. So the final goal in the digitization of the selection of epigraphical monuments is to provide access to interesting but inaccessible inscriptions, give the viewers the ability to see them from many different angles and allow for the opportunity for direct engagement.

\textsuperscript{20} It is not possible to classify these inscriptions as \textit{in situ} due to past excavation techniques which moved some of the objects into places where previous archaeologists believed they should have existed. For example the so called casino fount (no.84) which currently is sitting in the so called casino was moved to that location at a previous date because it looked like it belonged in a casino. Now the so called casino is thought to be another basilica or episcopal residence because of its proximity with the episcopal basilica, which would undermine the theory that the casino fount belongs in the casino.

3. Enhancement Methods

3.1 Photogrammetry

Photogrammetry is most commonly defined as “the science or art of obtaining reliable measurements by means of photography in order to determine primarily geometric characteristics, such as size, form, and position of the photographed object.”22 The practical applications range from aerial mapping and geographical feature analysis down to microscopic measurement. There have been arguments since the early 1980’s to use photogrammetry at archaeological sites and excavations based on its merits to enhance the recording of data in the field, especially due to its non-destructive characteristics.23

The photogrammetric process consists of taking a series of photographs that overlap in some way in the attempt to achieve parallax and plot 3D points in space based on the depth information obtained from it.24 In digital photogrammetry, the result is achieved through triangulation between points in space and their corresponding representation on a camera sensor in different positions, with many variables factored in to account for distortion in the camera and lens and the camera’s position in space. Before the advent of digital photogrammetry, analog stereo photogrammetry had two basic stages in the workflow; the photographic stage which is

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done with a film camera on site and the plotting stage which was done later with an analog stereoplotter in a drawing laboratory [Figure 2]. The separation of these stages allowed for some advantages but created visible disadvantages when compared to traditional recording systems, mostly due to the large time variance between the photograph capture and the plotting stages and that the photographer and plotter’s roles were specialized in that they would not be performed by the same person which led to discrepancies in the data.25 There are still two main stages in the modern digital photogrammetry process, beginning with the digital photographic capture stage and ending with the computer processing stage using a photogrammetry suite software which replaces the analog stereoplotter. The mapping and analysis process is significantly less time-consuming and user friendly with digital photogrammetry due to the elimination of the stereoplotter. Similar advantages are true with the recording stage because of new digital cameras. The technique has only become faster and more reliable as the roles of the photographer and digital technician are now often performed by the same individual instead of two separate roles where miscommunication could lead to suboptimal results.

The switch from film and analog to the digital system is what has driven the cost of photogrammetry down and allowed for the technique to be applied in the scientific archaeological sector. With even the most basic consumer level DSLR camera and a low-cost research license of a photogrammetric processing software, one can produce photorealistic 3D models of artefacts to a high degree of accuracy.

The advantage of digital photogrammetry for recording archaeological data is the ability to produce a 3D model of an object that is accurate in relative size and proportion to a sub-pixel

degree, which captures more detail than the human eye can see. This is done through image matching, which is the finding of corresponding features or image patches in two or more images taken of the same scene from different vantage points, in a process that will be expanded upon below. Depending on the application and level of detail required, photogrammetry produced 3D data can be linked into geographical coordinate systems with absolute measurements to produce models with accuracies ranging from the sub millimeter in the manufacturing industry to centimeter accuracy in the architecture and construction industries.  

In some cases pixel-level accuracy is satisfactory, or depending on the sensing equipment and spatial resolution this is the greatest level of detail attainable. Sub-pixel accuracy is attainable and can be achieved through one of two approaches; either resample the image intensity to achieve a higher spatial resolution through interpolation or to interpolate the cross-correlation surface after the matching process at a higher spatial resolution in order to determine the peak correlation at sub-pixel precision.  

The basic principles of photogrammetry to determine the shape and position of an object is by reconstructing bundles of rays for every image in an overlapping image sequence, together with the corresponding perspective centre to establish the spatial direction of the ray to the corresponding image point. With this and the knowledge of the imaging geometry within the camera, such as focal length and sensor size, every image ray can be established in 3D space. Subsequently the intersection of two corresponding rays determines the object point, whereas in stereophotogrammetry two images are used in the processes and in multi-image photogrammetry the number of images used can be, in theory, unlimited. It is important to note that with current

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digital low-cost photogrammetry it is most often multi-image based photogrammetry which is often called ‘Structure-from-Motion’ or SfM.\textsuperscript{29}

There are two significant calculations used in the photogrammetry process to determine planar accuracy and depth accuracy of a project.\textsuperscript{30} The former is used to calculate the pixel size derived from a given camera and lens combination at set working distance. It is represented as:

\[
\text{pixelsize}_{\text{ground}} = (d \div f) \times \text{pixelsize}_{\text{image}}
\]

Whereas ‘\(d\)’ represents the distance between the object and the camera and ‘\(f\)’ represents the focal length of the camera and the \textit{image} pixel size is known either by publication from the manufacturer or derived from the division of size of the sensor by the maximum resolution of the camera. This calculation results in the known pixel size on the object’s planar surface but it does not represent the third dimension, depth accuracy. To determine depth accuracy another factor must be known in the equation, the ratio between the camera positions and the proximity to the object. The equation to determine depth accuracy is expressed as:

\[
\sigma_{\text{depth}} = (d \div b) \times \sigma_{\text{plan}}
\]

whereas ‘\(d\)’ continues to represent the distance between the object and the camera, ‘\(b\)’ or base, represents the distance between two camera positions and the sigma plan is known from the planimetric accuracy multiplied by the accuracy of pixels in the image sensor.\textsuperscript{31}

The photogrammetric process is comprised of three parts; first, the image acquisition, which as mentioned before is now almost exclusively done with digital cameras such as the DSLR, second the object reconstruction phase, which is performed with mathematical models


and photogrammetry processing software, and finally measurement and analysis derived from the resulting models.

The image acquisition stage happens in the field and is either categorized as close-range (on the ground) photogrammetry or as aerial photogrammetry captured from either a manned or unmanned aerial vehicle. The two aforementioned equations are used to determine what camera and lens set-up is appropriate to achieve a suitable level of detail for the project. At this time, if the 3D data is required to be georeferenced with absolute coordinates and scaled, the survey work must also be incorporated. To incorporate surveyed points and georeference the 3D data, features are chosen on the subject to be marked and then surveyed in with either a differential GPS, GLONASS, an equivalent satellite positioning system or a survey total station unit. The survey data is then transferred into the photogrammetry software, linked with either and the geo-positioned coordinates are assigned to their corresponding points on the images. Otherwise coded, centroiding or reflectorless survey targets can be used that improve the accuracy of the survey equipment’s measurement of surveyed points. The photogrammetry software then has the ability to link the surveyed point with the image reference point with a higher degree of accuracy due to the software’s ability to automatically detect coded target points which in turn eliminates the degree of human error that can negatively influence the accuracy of the project.

The image acquisition phase is the first and crucially important stage in the photogrammetry process because the models produced are only as strong as the photographs that produced them. If the underlying stereo algorithms used in the selection of the camera network

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stations are not sufficient to produce effective parallax or photo overlap then the models produced will be fundamentally flawed.33

Once the digital photographs are captured they are ingested into the photogrammetry software and then aligned via triangulated matching points or tie points through algorithms explained in the following paragraph. The initial alignment is then refined through resection and bundle adjustment iterations to calibrate the interior and exterior orientations of the model to achieve the level of accuracy required for the specific application.34 The resection procedure determines the final position and facing orientation of the camera when the picture was taken, while the bundle adjustment process is used to produce the final xyz coordinates of all the measured points. Through the elimination of identified bad points or uncertain points and the subsequent resection and adjustment, the camera calibration model is determined with greater certainty and the overall accuracy of the project is increased.

A series of six overlapping photographs, two 90º portrait, two 180º portrait and two landscape shots, allows for the specific camera, lens and focus set up to be calibrated easily by developing a camera model and parametrizing the distortion. Once the focus is set, along with the camera and lens pair, it too must remain a constant throughout the capture processes to not alter the defined calibration.

To construct the data the matching points the software finds between two or more source images are used to determine the exterior and interior orientations of the model. The exterior orientation values represent the camera’s position in space (x,y,z,) and its rotation (ω, φ, κ) relative to the subject at the time of the photo, or if surveyed measurements are taken then the exterior orientation values can be absolute. The interior orientation defines the internal sensor geometry of the camera and is used to parameterize and compensate for sensor and lens distortion. The interior orientation takes into account the principal point of the camera sensor, the focal length and lens distortion which can be established by the aforementioned six-image calibration process. With Photoscan the majority of this process is automated and for an experienced photogrammetry software operator it does not require a great amount of effort.

Based on the desired application modern photogrammetry software suites can produce data sets in varying formats as demonstrated in Figure 3. The first data output from the process is what is called a sparse cloud, which is a series of points that represent the matching points or ‘tie points’ the photogrammetry software has identified in multiple photos which are used to adjust and optimize the alignment of the photographs [Figure 4]. These matching points are chosen by the software through either semi-global matching (SGM) or normalized cross correlation (NCC). In the case of Agisoft’s Photoscan SGM algorithms are used and the algorithm works with a pair of images with known interior and exterior orientations and epipolar geometry finding patching points along independent one-dimensional paths through the image. Photoscan also takes into

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account the camera and lens information stored in the source image’s EXIF data to improve matching accuracy.\textsuperscript{37}

The sparse point cloud is a result of the SGM algorithm acting more liberally with the matching points, whereas the dense cloud data is more constrained but an amplified number of points is identified. The variance in quality that Photoscan can create of dense clouds is a variance between the initial parameters weighting to permit data adaptation in the image content and the resampling of images, with the higher quality data sets requiring more processing time and power. Both sparse and dense clouds are visualized as unconnected points in space with an x, y, z value and can be assigned an r, g, b colour value as well.

To form a more solid geometry, the point cloud points can be connected into what is referred to as a wireframe or a triangulated irregular network (TIN). This is done by indicating the edge with a continuous smooth line between the point cloud’s vertices. The data is then referred to as a mesh when the wireframe surfaces are filled to create polygons. In either case the surface reconstruction can be based on varying algorithms such as Delauney triangulation or Poisson surface reconstruction. These algorithms take into account the spatial positioning and orientation, based on vertex normals, to determine which point vertices to connect.\textsuperscript{38} Using Poisson surface reconstruction helps to eliminate noise that is created through the SGM process that would otherwise be apparent if the meshes were produced from connecting every nearest neighbour point.


Some photogrammetry software suites, including Photoscan, allow for the mapping of the photographic source image onto the mesh to create a U,V map and colourize the mesh. For many industrial applications point clouds are sufficient to perform various measurements but for cultural heritage documentation textured meshes (.OBJ + .MTL) of 3D data provide the most detail and simulate a photorealistic look. The .obj file format, or wavefront object, is a standard text/plain language file that represents the geometry definition of 3D graphics by the position of each vertex, and the vertex normal and the faces that define each polygon along their vertices. The .mtl file is the sister material file that represents the visual aspects such as the UV position and mapping of each textured coordinate vertex. Most 3D models that are produced serve most effectively as digital versions where they are in their most detailed state, which is the case for this project, however photogrammetry produced models can also be 3D colour printed for their physical archival storage.39

Analysis of photogrammetry produced 3D data takes a variety of forms of measurement practises with either relative or absolute referenced scale. Often times these measurements can be recorded directly in the photogrammetry processing software itself but sometimes additional software is needed to further manipulate and interpret the 3D data. Measurements from 3D photogrammetry models include single point measurements, geographical plotting in the manner of mapping survey referenced 3D data in GIS systems, volume measurements, point-to-point distance measurements, surface definitions, comparison against machine control data and

rectification/orthophotos.\textsuperscript{40} A majority of these measurement techniques have applications in the archaeological field with the ability to digitally record measurements of fragile or inaccessible subjects, or to improve upon manual recording techniques of mundane objects. Furthermore photogrammetry produced 3D data can be transferred to CAD programs to be combined with other 3D data to produce a collective of data for highly accurate archaeological site-plan recording.

Specifically to this project, the camera that was used for the image capture of the selection of Stobi’s inscriptions was the Nikon D800E 36.3 MegaPixel CMOS DSLR camera equipped with the Nikkor AF-S 50mm f/1.4G lens. The number of photos that were taken for each model averaged from 10-25 depending on the size and degree of coverage of each inscription. The photographic process consisted of determining a suitable distance away from the monument to have the subject fill the camera’s frame to obtain the most data out of every photograph, determining the correct exposure settings, locking the focus in position and then moving the camera to achieve converging pairs of stereo images across the face of the inscription.

Included with each series of photographs of the monuments was a custom printed scale bar that was used to assign absolute scale to each of the models individually [Figure 5]. The scale bar consists of two coded targets that are automatically detected by the photogrammetry software, two large centroiding targets and sixteen smaller centroiding targets. The distances between the centres of all of these targets in relation to one another are known and that is how

\textsuperscript{40} Luhmann, Close range... : 11.
scale can be applied to the 3D model. There was no additional survey equipment used to reference the models to real world geographical coordinates.

The Russian-made Agisoft Photoscan was the software used to produce the models of the inscriptions. There are several benefits to using this program over other more complicated photogrammetry software suites. With other SfM photogrammetry suites, Photoscan allows for the use of non-metric cameras while still maintaining high degrees of accuracy, which allows for the use of DSLR cameras and drastically reduces the cost of photogrammetry. Another advantage is that the workflow is relatively straightforward and if the initial photography is performed correctly much of the workflow can be automated. It is a relatively inexpensive software package compared to other photogrammetry software suites and because of this it has driven its popularity and led to the developers continually and frequently updating the software. As mentioned previously, Photoscan has the ability to produce high quality meshes and textured meshes from point clouds using Poisson surface reconstruction technique without the need for an additional piece of software and the complication as to determining which meshing algorithm to use. Photoscan’s ability to adjust the level of detail to be reconstructed, through either using the image at full resolution or image resampling, at both the point cloud and meshing processing levels, provides the opportunity to triage the processing power and time and subsequent data file size, to each unique project depending on the level of detail required for that specific project. This eliminates the step of decimating a high quality 3D mesh to a lower quality version in projects that do not require a high level of detail. This is often a necessity to keep polygon size

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down so that the detailed models can still be shared easily and viewed on basic hardware, smartphones and tablets. In the case of this project, the scale of the objects and level of detail that the 3D data retains resulted in each completed textured model requiring between 40 - 130 MB of data storage.

A final benefit of Photoscan, shared with other digital photogrammetry software packages, is its ability to export point cloud and mesh data in a variety of different formats such as OBJ, PLY, XYZ text file format, ASPRS LAS, ASTM E57, U3D, potree, PhotoScan OC3, and 3D PDF. These are essential in getting the 3D data to the end user in an interactive and valuable way without the loss of any information.

The Nikon D800E DLSR was selected because of its high resolution sensor and high quality optics which captures an immense amount of data and has the ability to produce extremely detailed models. The detailed models produced from this camera not only serve as a high quality digital record but allow for the computational analysis of depth mapping that would otherwise be ineffective with lower resolution models.

During the principal photography some issues arose in the field at Stobi. The first problem which was encountered was with the inscription monuments that were located in an uncontrolled setting in the field such as inscription numbers 16, 36, 64, 84. The inability to control the capture setting meant that at times extraneous materials obstructed the subject in parts

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44 Van Damme."Computer Vision Photogrammetry for Underwater Archaeological Site Recording in a Low-Visibility Environment." 232; Explains additional benefits such as the ability to optimize the cameras without the need to have a specialized IT background or strong technical knowledge of resectioning, bundle adjustments and other photogrammetry principles.
from varying vantage points such as grass, trees, dirt and debris and some photographic angles had to be sacrificed. In the occasions where debris could not be removed or avoided such as grass or soil it resulted in errors in the model around the edges of the inscription stones being meshed into their background’s surroundings.

The second challenge faced was equipment malfunction caused by the extreme heat environments in the field. The prosumer level D800E, while exposed to direct sunlight in the hot Macedonian summer, which would reach temperatures in the thirty to forty degree celsius range, would cause the camera to overheat and cease to function. This led to additional time being required to allow the camera to cool and restart the photogrammetry capture process as the camera would often cease to function midway through photography and disrupt the established calibration. This problem was overcome by regularly pacing the camera’s exposure to direct sunlight and shielding it during the capture process with shade from an umbrella.

To summarise, digital photogrammetry has many advantageous qualities over traditional recording methods for epigraphy and they are more significant than simply being the fastest way to capture the most amount of data. Not only will digital photogrammetry capture all of the data on a monument or inscription that you deem relevant by sight but it will also capture everything in its visible range which can expose hidden elements not deemed relevant at first inspection. Secondly, it is entirely objective without any opportunity for wishful thinking or artistry; if the information was not already present it cannot be recorded. Beyond that, the technique is known for its high degree of accuracy, it is entirely passive and does not require the monuments to be
disturbed at all. Finally it is a genuine 3D record that allows for the re-interpretation of the archaeological record at any later date which is not possible with conventional, drawn records.45

To improve documentation techniques to create an environment that has a complete compositional feel as opposed to multiple individual items segmented and placed into one environment, it is important to implement HDR photography into the photogrammetry capture process. Without HDR photography for photogrammetry the models in the virtual environment can be shaded with the same intensity and direction but the individual colouring of the models will portray incorrect colour information. HDR photography will ensure that a proper diffuse map can be created for each model’s texture so that when they are all placed in the same virtual environment it is that environment which determines the colour, strength and direction of lighting. In this way all of the models will appear to be lit by the same source and feel like they are in the same environment, instead of the colour variations and intensities that are reflective of the original principal photography conditions.

For example if the principal photography took place for one inscription in the shade in the afternoon sun, its material texture colour will be based on the lighting conditions for that specific moment. This produces a seemingly fake result when relit in a virtual environment with another object that was captured in the open on a sunny day. Although being much more time consuming, implementing HDR photography into the photogrammetry workflow eliminates the necessity to have the same lighting conditions for every monument captured.

3.2 Depth Mapping

The process of depth mapping of 3D inscriptions is best comparable to the digital version of an inscription rubbing. It involves the use of a highly detailed 3D point cloud or mesh of a surface that can be fitted to a common shape acting as a reference point and then distances calculated between the two surfaces.\textsuperscript{46} The calculations from real data to the reference model can be in the form of a point cloud-to-mesh or a mesh-to-mesh distances.\textsuperscript{47} This process was initially developed for the aerial laser scanning and terrestrial Light Detection And Ranging (LiDAR) industries for purposes of change detection. The open source software CloudCompare is frequently used to do depth mapping processes.

In the case of depth mapping epigraphy, either a median depth plane of the inscription surface is calculated or a smoothed poisson-derived surface is fitted to the inscription facade in CloudCompare. Then the depth deviation of the photogrammetry produced 3D data and the median plane is calculated. The result can serve to identify deviations at the sub-millimeter level, well beyond what can be identified by the human eye.

The information that is derived from the depth-mapping deviation analysis is displayed as colour scaled mesh, which is called a scalar field and it is a ‘heat map’ representation of the degree of deviation. This is often represented as blue-green-yellow-red, whereas blue indicates the most extreme negative depth deviation to red indicating the most positive depth deviation.

The mean plane’s initial fit to the facade of the inscription can be determined one of three ways; a basic ‘average distance’ of each point or vertex and its nearest neighbour, the ‘best


fitting plane orientation’ in which a least square plane is computed through every point, and the ‘Hausdorff’ distance’ which represents the common distance between two sets of points. Although the Hausdorff distance plane is often more precise than the two previous methods it requires much more computational power and a satisfactory result can be obtained from the best fitting plane with reduced processing time. The best fitting plane method accounts for error as it attempts to fit to the natural curvature and deviation of the inscription plane and it avoids generating a false negative that would occur with using a simple 2D geometric flat plane cut through the inscription facade. The second solution to eliminate error and false positives is in restricting the display parameters in the CloudCompare software. The deviation range can be restricted to display only values greater than a set established depth, which in combination with knowing the planar accuracy of the photogrammetry produced 3D model and the limitations of the equipment used to produce the model, can remove false positives that would be in the size range greater than what the equipment is capable of sensing.

Along with basic depth mapping, ambient occlusion effects can be added to the 3D data in CloudCompare. This filter simulates global illumination, or lighting from all directions and simulates the increased contrast of the shadows by objects blocking the ambient light; the increased contrast then aids in the deciphering of lettering for epigraphical study. For a comparison of the various depth mapping techniques see Figure 6. The final result of the depth mapping process can be used to produce an image with increased contrast that both enhances the legibility of currently legible inscriptions but also in cases can provide a legible result for previously illegible monuments.

3.3 Reflectance Transformation Imaging

Another tool the origins of which can be traced back to video game development is that of Reflectance Transformation Imaging, known as RTI. It was a technique developed to obtain high quality surface normals of objects to be ‘baked’ onto simple low-poly geometry to create the appearance of complex lighting and geometry. This process, which is also called UV mapping, allows for video games to mitigate the number of polygons taken from their limited polygon budget for textured objects such as walls while still maintaining a realistic and immersive environment. While there are methods to derive surface normals for the purpose of low-poly baking from complex 3D models, even those produced by photogrammetry, in most cases RTI produces a more accurate surface normal map that is free from potential error introduced through surface mesh reconstruction processes. RTI can be described as a method of generating surface reflectance information using a comparison between images with a fixed camera perspective and varied lighting positions.

RTI alone can be a useful tool for virtual archaeology in a number of applications such as recording worn coins for numismatics, brush stroke analysis for frescos as well as epigraphical recording and study. Some specific examples include the use of RTI to enhance the documentation of a set of coins from the Hospice of the Grand St. Bernard, where it was found

51 Merlo,"3D model visualization enhancements in real-time game engines.": 183.
that RTI allowed for much greater detail to be recorded from the coins and that it provided a more complete interactive experience of the data set.\textsuperscript{53} Another practical application was again work done by Mark Mudge and Tom Malzbender in their use of RTI to enhance the documentation of archaeological rock art from the limitations of hand-drawn graphics and digital photography to interactive, multi-use 3D recording.\textsuperscript{54}

Its value as an analytical tool is derived from its ability to detect minor variations in the surfaces of objects by producing a surface normal map. A surface normal map, also referred to as a bump map, is used to simulate the appearance of detail of a 3D mesh without the need for additional polygons through dynamic relighting. It is most commonly represented as a RGB image where the RGB components correspond to the XYZ coordinates where a normal pointing directly perpendicular towards the viewer is represented as light blue and a completely blue image would represent a completely flat surface. See Figure 7 for the varying colour representations.

The RTI process itself is divided into two parts. The first is the photography stage [Figure 8]. There are various different ways to conduct RTI photography such as using light rigs and light domes, but the underlying concept remains the same.\textsuperscript{55} A camera is placed on a tripod


and remains in the same position for multiple exposures, and while the camera remains stationary, a portable flash unit or other independent light source is moved to many positions in a hemispherical dome around the subject. The distance that the light source is held from the subject is based on the inverse square fall off principal, in that a light source held beyond two to three times the diagonal surface distance of the subject will lack the necessary intensity to be a useful light spot position. After capture in a highlight-based RTI, compared to a light-dome produced RTI, the moving light positions are recognized by the software by detecting highlights on a stationary black sphere which is linked to each photograph. The series of exposures are then combined in the RTI building software to produce a surface normal map. The goal from this process is to quickly obtain the reflectance and 3D shape of the imaged surfaces and to obtain accurate surface normals to further explore the shape’s surface.

RTI data can be produced as a model with either polynomial texture maps (PTM) or hemispherical harmonics (HSH). The PTM technique was first developed in 2001 by Malzbender where it was demonstrated that the intensity distribution over all angles of a hemisphere above a fixed object could be estimated by a biquadratic function with six varying parameters. This is done with an equation that can represent arbitrary geometric shadowing and diffuse shading across a planar surface. HSH is an improved method introduced in 2004 by

56 Due to the restrictions of RTI in the field and the size of some objects a full hemisphere of light positions around the subject is not always possible. In these cases the light source is moved to as many positions as possible to create the fullest hemisphere that the field conditions allow for.

57 Earl, "Reflectance transformation imaging systems for ancient documentary artefacts." :150.

Gautron which uses the transformation of Associated Legendre Polynomials to a full spherical representation.\textsuperscript{59}

The surface normal map can be used independently in the RTI viewer application to move and manipulate the light source to achieve different shadow and highlight effects which can increase the legibility of faint inscriptions and small surface variables. The RTI viewer application also allows for various filters to be applied such as diffuse and specular enhancements which have varying effects on the lighting conditions and in turn affect the legibility of objects [ Figure 9]. The specular enhancement filter modulates the Phong shader model to increase the specularity by enhancing the magnitude of shadowing and highlights. It turns the diffuse elements of the RTI off and turns the data into an ideal mirror adding the most natural reflective elements, which in turn, aids in increasing the legibility of texts by increasing the contrast of the model.\textsuperscript{60}

By adjusting the lighting position on the RTI produced surface normals different elements of the text on inscriptions can be seen, but it is often necessary to move the light source to multiple locations to achieve legibility on all of the text in study. The RTI viewer software also allows for multiple viewpoints to be stored as screencaptures, so that a user can share the light position perspectives that demonstrate the greatest legibility.

There are some issues that can arise in the capture and processing of RTI data. Aside from the technique being cumbersome and time-consuming to perform in the field, errors in the RTI data can arise as colour and intensity variations from self-shadowing, sub-surface scatter and


interreflections. These elements are captured and modeled and can produce false positives and distort the data.

Although RTI has its merit as a standalone application for the study of epigraphy, the greatest effectiveness of this technique is when it is used in combination with other 3D modeling and virtual heritage processes that can give it full 3D object context and surrounding environmental context. The delivery of RTI data also remains problematic. Only one application, RTI viewer, can open .rti files and while the application is open-source, the hardware compatibility issue continues. Disseminating the RTI data over using a standalone web application has proven to be slow because the large file size produced usually requires down-sampling of RTI datasets. In this project the average .rti file size ranged from 300 - 500 MB. Naturally the proposed solution for this would be the virtual lapidarium which would in addition to giving the RTI data full objective 3D context and environmental context, would also allow for a simplified but still highly detailed web solution.

3.4 Panoramic Virtual Tour

Panoramic virtual tours have become an emerging trend in virtual heritage documentation since the late 2000’s as consumer software to create personalized virtual tours has become more readily available. The introduction of the Kolor Panotour Pro software in combination with the Kolor AutoPano Giga software has allowed for virtual heritage experts to craft customized

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61 Malzbender, "Polynomial texture maps." 519-528.
62 Earl, "Reflectance transformation imaging systems for ancient documentary artefacts." 151.
63 Gabriele Bitelli, Maria Alessandra Tini, and Luca Vittuari. "Close-range photogrammetry, virtual reality and their integration in archaeology." Proceedings of XIXth Congress of International Archives of photogrammetry and remote sensing, 2000: 876. Bitelli was using QTVR (quicktime virtual reality) as early as 2000 for virtual tour documentation of archaeological sites and integration of 3D assets into such a tour. However due to the limitations of the early technology the QTVR are not true virtual tours but instead are interactive videos with limited control and the 3D assets that were integrated were not true 3D web published assets.
virtual tours of heritage sites for research, documentation, preservation, tourism and information purposes. They behave similarly to Google’s technology in their Google ‘Street View’ application where a user can move freely throughout an area based on moving to various panoramic sphere locations. Visual appeal, interactivity and the ability to incorporate different forms of data are the extent of panoramic virtual tour’s capabilities and any analytical study with the photospheres alone is limited. They serve more to create a digital record of what the site or area looked like at that specific moment in time when the photos were captured. Given that it is in essence a photographic record it cannot be scaled and therefore no measurements can be taken from it. Yet in combination with the other aforementioned virtual heritage techniques it has great value to the archaeologist as well as the conservator who utilizes digital techniques.

Panoramic virtual tours have already proven to be an effective tool in archaeological recording as what Koehl deems as an ‘Archaeological Knowledge and Information Systems’ (AKIS) because of their ability to have multiple information elements stored in them. Using Kolor’s Panotour Pro as well, Koehl reported that their project allowed for the demonstration of convincing results that an audience of historians and archaeologists were able to access interactively online providing both localized and contextual information.

The theory of 360º or multi-image spherical panoramas was developed by Szelisky in 1994 where each point is covered by multiple photos, partially overlapping around a single point.

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rotating centre. The sphere is often mapped in a cartographic plane projection with the 
latitude-longitude represented with angles expressed in radiant as in the expression:

\[ x = r \theta \quad e \quad y = r \varphi \]

In which \( \theta \) represents the horizontal pixels of the sphere divided by the radius and \( \varphi \) is the 
vertical pixels of the sphere divided by the radius.\(^{66}\) There are many different panoramic stitching 
software available but for this project Kolor’s AutoPano Giga (APG) was employed. APG uses 
the Scale Invariant Feature Transform or SIFT extraction to select matching points in various 
photographs to serve as key-point anchors to link photographs together in a seamless mosaic. It 
is able to extract distinctive invariant features from images invariant to scale and rotation and it 
works well to find points accurately and quickly. It consists of four major stages: scale-space 
extrema detection, keypoint localization, orientation assignment and keypoint descriptor.\(^{67}\) This 
proves to be useful in complex panoramic scenes where confusing elements, such as repeating 
textures, or warped geometry from the use of fisheye lenses needs to be accounted for.

To ensure that the panoramic spheres are stitched without errors, beyond what SIFT is 
capable of, the no-parallax point (NPP) must be found for each lens and camera combination 
being used in a project. Parallax is defined as the difference in visual position of an object 
viewed along two varying lines of sight and measured by the angle of inclination between those 
two lines. This can be understood as two objects being lined up perfectly behind one another 
from one viewing perspective. When the viewing perspective moves along the horizontal axis 
there is a parallax effect if the two objects appear to be moving across from one another and a 
no-parallax effect if they stay consistently behind one another.

The NPP is found by aligning the camera with two objects and adjusting its rotational axis either forward or backward through the lens until there is no visible parallax effect while looking through the viewfinder. After finding the NPP, the camera is meant to rotate around this axis throughout the panorama. Without accounting for this in panoramic photography, as the camera moves there will be a parallax effect and it will distort the image stitching. Due to the geometry of lens and the lack of a fixed entrance pupil, fisheye lenses do not have a true NPP but instead a point of ‘least parallax’ and this is right at the front of the lens element.

In the case of the virtual lapidarium of Stobi’s epigraphy, the virtual tour will serve as the backdrop to the epigraphy to give the viewer important spatial and contextual data of the epigraphical objects, as opposed to the presentation of floating, 3D objects independent from situational information or context. The virtual tour also allows visitors to access previously inaccessible portions of the site of Stobi and its buildings, such as under the mosaic floor in the Episcopal Basilica which reveals the earlier second century BCE structures.

The photographic process to capture the 360° Panoramic Virtual Tours is different than that of the other photography processes outlined in this paper and requires a different set of equipment. The cost of this technique is lower than that of RTI and photogrammetry because it requires only four basic elements; a tripod with an attached panoramic head mount, a fisheye lens and a consumer level DSLR camera that can be of a lower resolution than for RTI or photogrammetry applications as there is no 3D data being recorded.


In the case of the panoramic virtual tour of Stobi a Canon Rebel T1i DSLR camera was used along with a Vivitar f/4 7mm crop sensor fisheye lens. The 7mm Vivitar lens when mounted on a crop sensor camera, such as the Rebel T1i, has a diagonal field of view of 180°. To achieve as close to a full spherical 360° panorama as possible, the camera was placed in the portrait orientation, so that the greatest field of view was from the top of the frame to the bottom. This is done so that when placed on the panoramic head only one row of photographs is needed to achieve a full spherical effect, which both reduces the time required to capture each 360° sphere, process the data, and reduces the file size required to store the data. Without a multi-row panorama head, the zenith and nadir areas of the 360° cannot be included, so the actual dimensions of the panospheres is 180° x 146°. Similar results are possible to achieve when using a lens longer than a fisheye, although they require an additional multi-row panoramic head. The restricted field of view requires more images in more camera positions and therefore increases the time required for the photography and the file size. To create the full 360° panoramic sphere with the camera in portrait orientation it was rotated at 45° increments. After 8 positions there was 15% overlap in each image which is sufficient for AutoPano Giga, the panoramic stitching software to stitch the images into one seamless panorama without any errors or occlusions [See Figure 10]. The final photosphere that is created is a 11822 x 4519 pixel image which is equivalent to a 53.4 MP image [See Figure 10.1]. At this resolution there is a high level of detail captured in each scene but it still does not require a high amount of data storage.

High dynamic range photography or HDR photography was implemented into the photographic process of the panoramic virtual tour creation. HDR photography is described as the ability to see the brightest highlights and darkest shadows correctly exposed in the same
image by combining multiple images with different exposures. Traditional photography is considered low dynamic range or LDR photography because it captures a photograph at only one set exposure. This means that in a scene with complex lighting, such as a bright day casting strong shadows in a shaded area, that only certain elements of that scene will be exposed correctly leaving other elements either completely overexposed or underexposed. HDR was first conceived to obtain improved illumination of real-world scenes in 1993. It was then used to obtain improved illumination for computer based rendering using natural lighting shown in Paul Debevec’s work.

Dynamic range considerations are particularly important based on the fact that the majority of archaeological field recording is taken outdoors in an uncontrolled setting. A typical digital camera sensor can only represent a contrast ratio of around 1000:1 and with harsh directed sunlight a typical outdoor scene may have a contrast ratio of 70000:1 between its darkest and lightest elements. In this scenario a single LDR photograph would lack significant detail on either spectrum in the scene. At the site of Stobi it was not possible to control the lighting of the various scenes of the site, as it was always shot using natural light and to retain consistency between the varying outdoor and indoor scenes HDR photography was used. This was done using a 3-bracket exposure with a +/- 1 EV (exposure value) at each camera rotation and then the multiple exposures were fused together using the Photomatix Pro HDR software,

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creating an evenly lit image exposing both the shadows and highlights of every scene [Figure 11]. With the little time and effort required to capture HDR photographs and their immense improvement in the exposure recording of a scene the benefits of HDR for archaeological applications should be clear.

To create a panoramic virtual tour that covers the entire site of Stobi and its twenty major buildings and locations three hundred and fifty nine HDR 360° panoramic spheres were captured. With the Kolor PanoTour Pro software they were linked together with over eight hundred hotspots that allows visitors to navigate through the tour. These hotspots in the interface can also direct visitors to different URL addresses, HTML pages, digital PDFs, and videos which further demonstrate the viability of virtual tours to be a central house information system for archaeological sites [Figure 12].

To enhance the visitor experience a 4089 megapixel aerial image was captured and downsampled to include in the tour to provide visitors with a top-down contextual idea of where each building is located in relation to each other. This image was produced with the robotic multi-row panoramic GigaPan head. Calibrated to work with the Canon Rebel t1i and a 200mm lens, the GigaPan was set to move along the NPP of the camera and lens combination and instructed as to the horizontal and vertical field of view limitations of the lens. The GigaPan was then programmed to photograph the extent of the specified scene and the images were ingested into AutoPano Giga to create a large-scale stitched landscape photomosaic. The advantage of using GigaPan images for archaeology is that they provide an efficient way to capture a large

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scene in the field at a very high resolution. The final result of the virtual tour that was produced is a 2.38 GB HTML file that is compatible on the web and easily shared and viewed by visitors internationally.

### 3.4 Web Presentation

The recent development of WebGL based 3D model plug-ins is what has allowed for panoramic virtual tours to be used as a viable setting for hosting 3D models as a virtual lapidarium. WebGL or WEb Graphics Library is a JavaScript API used to render interactive 3D and 2D graphics within internet web browsers without the need for additional plug-ins or external applications. Because of WebGL development, as long as individuals have access to a compatible device and an internet connection, they can experience and interact with 3D data without equipment, cost, or knowledge restrictions.

To employ the ability of WebGL technology individual 3D models must be uploaded to a 3D model hosting service, such as Sketchfab, or deployed through internal servers using source code such as Potree. WebGL has been used to produce a sort of digital archive of photogrammetry and LiDAR produced cultural heritage 3D data in the case of CyARK, which was founded in 2003 with the goal of digitizing cultural heritage sites in an attempt to preserve them for future generations before they are lost to unforeseen circumstances. While CyARK does have an extensive database of 3D data of cultural heritage sites, there are a few fundamental

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flaws in the data's presentation. Within their web publication only low polygon or ‘soft models’ are used and they lack significant detail. In addition, the mobility around the models is completely restricted to only rotational panning. There is no ability to download a higher quality model for further detailed study nor is there any option to upload one’s own 3D data of cultural heritage sites. Sketchfab, however, is a complete service that facilitates the sharing of 3D data across the web with significant features such as full model mobility control, the ability to dynamically relight models within the browser, the feature to download a high quality version of the model for further study and a lesser restriction on the number of polygons a model can be comprised of. This service is already in wide-use amongst hobbyists and scholars in the field of archaeology as a tool to publish and display 3D data.77

The restrictions of this technology is the speed of data transfer across the internet which limits how large an individual model can be and the unknown limitations of end-user VRAM graphics cards and hardware that restricts the detailed number of polygons they can render when the data is freely published. Long computation times due to high-resolution imagery or conversely data that has been decimated to such an extent that it no longer retains enough detail to be valuable can turn individuals away from employing WebGL methods to display and interact with archaeological 3D data at the scholarly level.78 Cosmas recognized in his paper the difficulty in using internet based platforms in that the developer cannot make any inferences as to the end-user’s hardware compatibility and so the visualization system has to automatically

adapt to the available bandwidth and graphics capabilities to avoid user frustration due to long delays or errors.  

The proposed solution for avoiding low quality models that would be published to circumvent unknown graphics limitations of end-users, is the combination of RTI normals data with photogrammetry produced models to achieve a model with a low enough polygon count to be processed quickly but retaining high quality normals data to still have the ability for strong analytical study of the models. The challenge in combining the two different types of data stems from the fact that the RTI imagery and photogrammetry collected imagery is often captured at different times with differing camera equipment resulting in differing UV maps for the photogrammetry produced .mtl texture files and the normals maps produced by the RTI. To properly align the normals with the material texture both images are ingested into ImageJ, a open-source computational photograph processing software, and the SIFT feature extraction is used to find matching key-points in both images. Then the points are used in bUnwarpJ, an elastic image registration plug-in, to align the source RTI image onto the photogrammetry produced texture map. This image is then saved after minor fringe adjustments are made in photoshop and used as the replacement of the .mtl texture for the .obj model.

The inscription models from Stobi, after being mapped with the RTI normals, were uploaded to Sketchfab to be hosted for public interaction. They were then subsequently placed within the 360º Virtual Tour as interactive web-boxes at the locations where they were found at

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the site [Figure 13]. Placing the epigraphical monuments in their locations in the tour is complicated by the fact that many of Stobi’s epigraphical monuments, even some included in this study, are no longer in situ and instead a form of anastylosis has occurred where prior archaeologists believed the inscriptions were intended to be located but not always done with enough information to securely determine that the moved location is the correct one. No such virtual anastylosis has been done in this study, instead the 3D models were placed in the tour according to their current locations at the site. When it was not possible to place the inscriptions in their original locations in the virtual tour due to their relocation to storage areas that were not included in the tour, the models of the inscriptions were placed in the virtual tour at the location where Stobi’s displaced monuments are held on site. This gives context to the surroundings of the inscriptions, their current state of preservation, and the history of the archaeological conservation methods used on the site.

4. Results of Enhancement Methods

The following section is a list of each unique inscription of the sample selection and the results of their digital enhancements. Depending on the level of deterioration and the conditions for photography in the field, RTI or digital photogrammetry was used to achieve the best result for digital preservation and legibility enhancement [Figure 14]. The method behind each decision to choose the techniques will be explored on a case by case basis. This study in the digitization of Stobi’s epigraphy was not intended to make new discoveries but instead to focus on high quality documentation and digital preservation. For the following examples each follows the structure of description, the publication transcription in black text, the newly interpreted transcription in red text, and conclusion remarks. The building numbers stated are in reference to

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the site map of Stobi and its list of buildings [Figure 1]. The translations for each are taken directly from the publication.

4.1 N. 10 Asclepios, Hygieia and Telesphoros

The inscription number 10 dedicated to Asclepios is a white marble rectangular slab (h. 0.63-0.67, w. 1.44, th. 0.17) that has been cracked into three major pieces and one small fragment [Figure 15]. It was first excavated in 1970 as a reused mullion column in the west end of the south aisle of the Episcopal Basilica (building 2). The state of the Greek inscription on the surface is very poor, with only a few words discernible in the middle and right sections, and traces of lettering visible on the left section. According to the edition the inscription reads;

233 CE

[------------------ Ἄσκλη]-

πιώ καὶ Ὑ[γ]ιείαι καὶ Τελεσφό-

[π]ωι τὰ ἀγάλματα Κλ(αύδιο) Κάτυλλ(ος),

Θήρων, Γάλλος, Σκύλαξ· ἀνετέ-

η ἔτους π· τ´ [κ]ατὰ δὲ Ἦρωμα[ουσ]  

[Μα]ξ̣ίμωι καὶ Π̣[α]τέρνωι ὑπά[τοισ].

[------------------ Ἄσκλη]-

πιώ καὶ Ὑ[γ]ιείαι καὶ Τελεσφό-

[π]ωι τὰ ἀγάλματα Κλ(αύδιο) Κάτυλλ(ος),

\[\text{81 I.Stob 24}\]

\[\text{82 I.Stob 24}\]
Θήρων, Γάλλος, Σκύλαξ∙ ἀνετέ-

θη ἔτους π · τ’ κατὰ δὲ Ῥωμαί[ον]

[Μα]ξίμωι καὶ Πατέρνωι ὑπάτοι.

[To ---] Asclepios, Hygieia and Telesphoros Claudius Katylos, Claudius Theron, Claudius Gallos and Claudius Scylax set up statues in year 380, for the Romans the year when Maximus and Paternus were consuls.

It is currently in protected storage in Stobi's Old Museum, not located on the map but found beside the north east entrance gate. With such a faint inscription and little other interest to the flat monument, RTI alone was chosen to record and enhance the object. The result from the RTI on the left side of inscription has recovered the text on the first half of the first line and the entirety of the final two lines [Figure 15.1, 15.2]. On the right two sections the RTI has produced enough contrast in the text for all of the lines of text to be legible. Other than being a principal example for the merits of RTI in documenting epigraphy, there is nothing more to remark about this inscription. The RTI normals have been ‘baked’ onto a rough geometric rectangle to represent the object in 3D in the virtual lapidarium without adding complex polygons but still retaining all the relevant textual information.

4.2 N. 16 Deus Caesar and Isis

The monument number 16 entitled Deus Caesar and Isis, based on its formula as the same structure for the cult of Isis in Stobi, is a greyish-rose marble rectangular slab (h. 1.47, w. 0.88, th. 0.45) that is thought to be a dedication inscription for the temple of Isis also located at Stobi. It was originally excavated in 1977 and its current location is in the southwest corner of the apsidal room of the Episcopal residence (building 2) and it lays along its long horizontal side with the right edge of the text buried in the ground. At the time when the inscription was
photographed for publication the stone was unearthed to fully reveal the inscription and since then part of the inscription has been covered by earth. The text is almost entirely legible and reads as follows;

Times of Domitian

Deo Caes(ari)

and after

et municipio

Stobensium ·

sacrum · Isidis · T(itus) · Fl(avius) ·

5

Longinus Augus -

vac. talis. vac.83

Deo Caes(ari)

et municipio

Stobensium ·

sacrum · Isidis · T(itus) · Fl(avius) ·

5

Longinus Augus -

vac. talis. vac.

To the god Caesar and to municipium of the Stobaeans, Titus Flavius Longinus, augustalis, (made) a sanctuary of Isis.

This inscription was chosen to be included in the case study because of the rapid deterioration of the marble and the inscription on it. Because the inscription is still relatively legible with the incisions deep enough to be visible to the naked eye, it was decided that

83 I.Stob 28
photogrammetry alone would be used in the documentation of this stone. The high quality model that was produced from 13 photographs had 5 million points and a textured mesh of 1 million faces. With a depth map analysis all of the textual information is preserved on the facade of the monument without the need to also conduct and RTI process [Figure 16].

4.3 N.36 Claudia Prisca and Priscila Dedication

The breccia statue base monument number 36 (h. 1.81, w. 0.84, th. 0.785) which is titled the Claudia Prisca and Priscilia dedication is from the imperial period and is currently in a severely damaged state with the assessment that its state will continue to worsen. It is titled this because it is a dedication to two mothers Claudia and Aelia, who are also mentioned in other inscriptions found at Stobi. It is not known where it was found or excavated but it now rests on the ‘Via Sacra’ by the North-west city gate (location 3). The inscription on the front face of the monument is framed by cyma recta and is entirely illegible to the naked human eye. The current publication photograph does not reveal any legible text to the reader and only shows its damaged state. This was the first monument in the study in which photogrammetry, depth mapping analysis and RTI were performed. Initially beginning with only photogrammetry and a depth map analysis of the model proved to not be effective enough to obtain all of the textual information from the surface of the monument [Figure 17.1]. The RTI produced a more legible result and contains more information than in the publication photograph yet it does not offer additional information than what is already transcribed [Figure 17]. As recorded in the Stobi epigraphy book the inscription reads:

Imp. period K[λαυ]δίωι
Πρείσκαι
καὶ Αἰλία<ι> Πρι-
οκίλαι Μευ-
στρία Πρίσκα
ταῖς μητρά-
vac. σιν. vac.⁸⁴

Κ[λαυ]δίαι
Πρείσκαι
καὶ Αἰλία<ι> Πρι-
οκίλαι Μευ-
στρία Πρίσκα
ταῖς μητρά-
vac. σιν. vac.

Meustria Prisca to the mothers Claudia Prisca and Aelia Priscila

From the RTI the entirety of the inscription is legible with the exception of the missing piece starting halfway through the ‘λ’ to the ‘δ’ on the first line. The high quality photogrammetry model that was produced had 3 million points and 693 thousand faces for the textured mesh. With the RTI Normals baked onto the low-poly (20 thousand faces) model the same legibility of the monument is achieved while hosted online [Figure 17.2].

⁸⁴ I.Stob 42
4.4 N.41 - 44 Gaius Aelius Priscus Statue Base Inscriptions

The inscriptions numbered 41 to 44 are part of a group of related inscriptions, dating second to third century AD.\textsuperscript{85} They are all semi-circular statuary bases (h. 0.28, w. 0.90, th. 0.55) with front-facing inscriptions. They are understood to be statuary bases because of the same pattern of two holes for statuary legs on the three visible monuments, with the assumption that the fourth follows suit. Monuments 41 to 43 are in storage to prevent further deterioration, while number 44 has been used as *spolia* in the North-west city wall tower. The first of the set that was excavated was number 41 which was excavated in 1972 and was reused in the Inner city wall and has since been moved from this position. The statue bases number 42 and 43 were both excavated together in 1974 found in the upper debris of the west room of the multi-storied structure. Number 44 was excavated in 2009 and found reused in a tower in the North-west city wall where it remains.

The monuments are carved in greenish sandstone which is highly susceptible to weathering damage. Monuments 41 and 42 and their respective legibility are in a more preserved state than monuments 43 whose right side face has flaked off and 44 which is exposed to the elements without any conservation or preservation. This set of inscriptions was chosen to be included as part of the study based on two factors, to produce models to monitor their varying states of preservation with special interest given to number 44 which exists with its inscription at a 180° rotation, and to produce a more suitable record of the monuments as the current publication photos do not present any opportunity to the reader to actually interpret any of the lettering of the inscription. The inscriptions are published as follows:

\textsuperscript{85} I.Stob 46-47
41. II-III cent. AD. \(\Psi(\text{ηφίσματι}) \beta(\text{ουλής καὶ}) \delta(\text{ήμου})\)  
Γάιον Αίλιον Πρεϊσκον  
πρειμπιλάριον. vac.  

42. II-III cent. AD. \(\Psi(\text{ηφίσματι}) \beta(\text{ουλής καὶ}) \delta(\text{ήμου})\)  
Γάιον Αίλιον Πρεϊσκον  
πρειμπιλάριον. vac.  

43. II-III cent. AD. \(\Gamma(\text{άιος}) \ Αίλιος \ Σεκούνδεινος\)  
τὸν πατέρα Περίσκον.  

44. II-III cent. AD. \(\Psi(\text{ηφίσματι}) \beta(\text{ουλής καὶ}) \delta(\text{ήμου})\)  
Γάιος Αίλιος Πρισκεϊνας  
τὸν πατέρα Περίσκον.  

\[86\] Longo 53

\[86\] I.Stob 44-47
According to the decree of the Council and the People (statue of) Gaius Aelius Priscus, primipilarius

According to the decree of the Council and the People (statue of) Gaius Aelius Priscus, primipilarius

Gaius Aelius Secundinus (arises a statue of) his father Priscus

According to the decree of the Council and the People Gaius Aelius Priscinus (arises a statue of) his father Priscus

For the entire set, both photogrammetry and RTI models were created [Figures 18 - 21]. A complete photogrammetry model, except for the underside of the monument which was too heavy to maneuver into a photographable position, was produced of the first inscription in the set. The intention behind this is that a complete 3D model of the entire stone is the most comprehensive documentation method for future study of all parts of the monument and is shown in this case to be a viable method of documentation. However in an effort to spend more time increasing the sample size only the front inscription facades were modeled for the remaining three inscriptions in the set as they are all similar in shape. Number 41 which had a
photogrammetric model produced of the entire monument rendered 30 million points and a textured mesh of 3.8 million faces. The other monuments in the set with only the facades having been modeled, rendered 3 million points and 531 thousand faces in the textured mesh.

The results of each modeling methodology produced a more complete and legible record than the original publication photos [Figures 18 - 21]. Because both the RTI and photogrammetry models were acquired, the RTI normal maps were baked onto the photogrammetry mesh models to produce a final interactive, scaled, true 3D model with a highly detailed surface rendering.

4.5 N.49 Legio IV Scythica

Inscription number 49 is titled Legio IV Scythica because it is the grave monument of Publius Porcius who was a veteran of the IV Scythic legion. It is a greenish sandstone grave stella that was originally excavated in 2010 reused in the late antique architecture next to the Eastern city wall and is currently preserved in two sections in storage. It has two distinctive grooves, a cylindrical hole in the top right corner and a rectangular groove along the right bottom corner, which suggests that this inscription functioned as a partial frame for a wooden door. The visible inscription exists in a recessed portion of the monument which extends from the top portion to the bottom. The visible inscription exists solely on the top half of the monument. The middle section of the monument, between the two remaining sections, appears to have the continuing text, is severely damaged and is indecipherable [Figure 22]. The inscription from the publication reads:

I cent. CE P(ublius) · Porcius
Here lies Publius Porcius, son of Publius, from the tribe Aniensis, veteran of the IV Scythic legion ---

To the naked eye there did not appear to be any text visible on the lower half of the inscription and after modeling and depth mapping analysis, this remained true [Figure 22]. The top section of number 49 produced a model with 1.5 million points and 574 thousand faces, while the bottom produced a model with 2 million points and 684 thousand faces. The RTI created from this monument produced a high contrast specular enhancement image which enhanced the detail quality of the photogrammetry model [Figure 22.2]. The goal with the 3D model of this inscription, because it remains fragmentary and in two separate pieces, was to digitally restore it and render it as a complete piece. After scaled digital 3D models of the upper and lower halves of the monumented were created, the two sections were aligned based on their geometry and edges to form a complete piece [Figure 22.3]. This is a more complete way of

87 I.Stob 56
documenting and digitally preserving the monument which is less difficult than aligning the fragments physically.

4.6 N.57 Gaius Aeficius Dedication

The Gaius Aeficius dedication is a grave stella with an ornamental figure carving on top of the base inscription. The greenish sandstone grave stella (h. 1.225, w. 0.75, th.0.17) has a large cracked section in the lower left hand corner. It was excavated sometime prior to 1970 in an unknown location and is currently being kept in the epigraphic storehouse at the site. There appears to be six lines of text and the inscription’s legibility decreases line by line down to the bottom where most of the face material has chipped away. The inscription from the publication reads:

I-II CE  C(aio) · Aeficio Maximo

L(uci) · f(ilio) Aem(ilia) · Sto[bi]s

mil(iti) · leg(ionis) · VII · C(laudiae) · p(iae) · f(idelis) · vixit

[a]n(nis) · XXV · meruit · an(nis) · V

5 [pos]uit · Tita · mater

[et] šibi [v]jva. · vac.\(^88\)

C(aio) · Aeficio Maximo

L(uci) · f(ilio) Aem(ilia) · Sto[bi]s

mil(iti) · leg(ionis) · VII · C(laudiae) · p(iae) · f(idelis) · vixit

\(^88\) L.Stob 55
For Gaius Aeficius Maximus, son of Lucius, from the tribe Aemilia, from Stobi, soldier of legion VII Claudia pia fidelis, who lived 25 years and was in military service 5 years, his mother Titia set (a monument) also for herself alive.

In the approach to document this monument photogrammetry was chosen to be the first documentation method because of the initial inspection and current well preserved state of the inscription and with the belief that a depth map analysis would be able to identify micro-variations left behind by the inscription process in the flaked off middle section of the inscription. The high quality model that was produced had 3.7 million points and 738 thousand faces in the textured mesh [Figure 23]. The depth mapping analysis proved not to produce an overly successful result so RTI was employed to produce highly detailed surface normals. The results from the RTI proved to be more successful than the depth mapping analysis and indeed revealed lettering in the middle flaked off section that had thought to have been lost, specifically revealing the certainty of the first ‘v’ and ‘i’ of viva in the last line, in addition to confirming the certainty of the other severely damaged section. In combination with the photogrammetry-derived 3D surface a comprehensive model was produced that records the ornamentation and the inscription of the funerary monument and enhances the legibility of the damaged sections.
4.7 N.64 Kalithchos Dedication

Similar to number 49, inscription number 64, the Kalithchos dedication, is a grey marble hexagonal dedication column (h. 1.99, w. 0.49, th. 0.41) also found broken and in two sections. The column was found beyond the outer North-west gates on the ‘Via Sacra’ (Building 3). The inscription on its front face reads:

II cent. CE

Καλίτυ-
χω Θεσ-
σαλωι-
κέο ἀδελ-
φος Ἄγα-
θόπους
μυιας χά-
ριω. Ὄς ἄν
[BREAK]
δὲ πιρᾶ-

5

ς τοῦ β-
ομόν, δ-
όσι το ιε-
ροτάτο
ταμίο δῆ-
In memory of Kalitychose, the Thessalonicean, his brother Agathopus. If somebody tries (to violate) the altar, let him give 1,000 denars to the holy treasury.
The inscription is entirely legible without any enhancement techniques. This monument was another example to demonstrate the technique of virtually reassembling an epigraphic monument from fragments. Similar to inscription number 49 the large marble pieces are difficult to move and would be unstable to reconstruct physically and restore it to its originally vertical state. To achieve the digital reconstruction two models were produced separately then aligned in 3D software [Figures 24 - 24.2].

In the publication the photographs show the inscription to be legible but the sections are cut and pasted together from two separate photos. Because of the ability to scale the 3D models in the photogrammetry applications the reconstruction of the two sections is possible in 3D and it can be virtually erected once again as a complete column. No attempt was made to interpret the shape or reconstruct any of the damaged areas of the column, only the currently existing data was documented and virtually reconstructed.

4.8 N.84 ‘Casino Fount’

Number 84 is a breccia octangular column (h. 1.14, diam. 0.57). It is the so called ‘Casino Fount’ because of its current location at the site of Stobi where it is found in the north section of the so-called ‘Casino’ (building 21). This area was part of a prior excavation where objects that resembled playing dice had been found and it was interpreted, in an unpublished report given by the local on-site archaeologists, to be a place of gambling and this octogonal fount to be part of this dice game. It is now the belief that this interpretation is incorrect and that this building was most likely another episcopal residence similar to the buildings surrounding it and that this monument was some sort of fount or altar.
It is inscribed on breccia and the front face has a slightly worn inscription which reads in the publication as:

II-III cent. CE

Αὐρηλία

Πλωτείωα

Τουτιλίῳ

Πρόκλῳ

Νέῳ τῷ ἑγ-

γόῳ μυει-

ας χάριν.⁹¹

Αὐρηλία

Πλωτείωα

Τουτιλίῳ

Πρόκλῳ

Νέῳ τῷ ἑγ-

γόῳ μυει-

ας χάριν.

_Aurelia Plotina in memory of her grandson Tutilius Proclus The Younger_

The publication documentation photograph shows most of the inscription’s detail and it is legible [Figure 25]. This monument was documented because of where it is currently located,

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⁹¹ I.Stob 67
exposed in the open and the fragility of breccia as a material under constant weathering exposure. Because of the current quality of the inscription and its legibility, only a photogrammetric model was produced. The high quality photogrammetry model for this monument has 2 million points and 480 thousand faces in the textured mesh. RTI model was produced to obtain detailed surface normals from the monument and was later combined with the photogrammetry model to digitally preserve the monument with as much detail as possible.

4.9 N.103 Artemidora Grave Marker

The final inscription in the study was number 103, the Artemidora Grave Marker. It is a greenish sandstone monument. On the face the relief field is shown without any ornamentation. The lower part is the inscription field which has a tabula ansata. The find date and location is not known for this monument and it exists now in a conserved protective storage space. The publication reads the inscription as:

Imp. period

\[ \text{'Αρτεμιδό-} \]
\[ \rho\gamma\ [\varsigma]\oversigma \]
\[ \text{τῶ ζιγδρῖ} \]
\[ \text{κα[ι ἐα]γη̣̣τη̣} \]
\[ [\muνήμης χάριν]. \]
\[ \text{Vacat}^92 \]

\[ \text{'Αρτεμιδό-} \]

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92 I.Stob 74-75
 vacat

There is no visible evidence of any inscription in the upper rectangular relief section of the monument. The inscription section that does exist is in a severely damaged and abraded state with few legible characters. This monument was chosen as a test case to determine the upper limits of photogrammetry, depth mapping and RTI as enhancement techniques for weathered inscriptions. An unenhanced view of the monument reveals almost no information about the text of the inscription and the specular enhancement does not provide much additional data [Figure 26]. The photogrammetry model produced had 2.7 million points and 543 thousand faces in the final textured mesh and is a better representation of the current state of the monument than the publication photograph [Figure 26.1]. The ambient occlusion filter applied in CloudCompare helped to reveal with minor certainty the ‘αυ’ in the fourth line [Figure 26.2]. Although it was not possible to produce much additional textual information in this case from the inscription with these techniques due to the damaging pattern and the material, digital documentation of the highest quality has been produced to preserve the sandstone inscription as it continues to deteriorate.

6. Conclusions

In conclusion, the virtual lapidarium created of Stobi’s epigraphy served as an example to how 3D data can now be useful to the unspecialized archaeologist, scholar and interested general

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public. With only moderate instruction required one can accurately produce 3D data using photogrammetry and RTI and with all of its elements combined it replaces the need for specialized software or expensive hardware. Having the data all stored and shared from a central location allows all of the 3D data to be integrated with 2D photographs and additional textual information in a single platform shareable solution. The combination of texture baking and game engine integration can be repeated across other archeological sites, and consolidate physical lapidarius and epigraphical museums. Having this interactive online solution raises cultural awareness of these historical sites and provides the opportunity for interaction with inscriptions which increases general interest and subsequently a renewed desire to fund their preservation. With this tool archaeological sites and museums are able to exhibit their entire collections that would otherwise be inaccessible because of storage issues and other conservation implications. These techniques not only make artifacts available to the public but provide the opportunity for viewing from all angles.

There are certain elements that should be improved upon in future projects using this methodology, mainly in the capture of images for photogrammetry. For this project the photogrammetry models were produced with LDR photos, but this led to differing colouring and shadow profiles between the models. Implementing HDR technique when capturing the photogrammetry photos would allow for a better diffuse lighting and the models would not feel disjointed when put together in a complete scene with differing lighting. Taking into consideration the previously mentioned necessary improvements on the existing technology the test case of Stobi’s epigraphy through the combination of digital techniques, the ‘virtual lapidarium’ has shown its validity as a stand alone end product to publish digital documentation.
This paper, using Stobi’s epigraphy as a test case, has demonstrated the utility of 3D documentation for archaeological finds and how through internet based solutions the 3D data that is becoming more readily available to the archaeologist, scholar and the interested general public can be easily accessed. In the future all of Stobi’s epigraphy should be digitized and digitally documented to be included in a larger, complete virtual lapidarium.
7. Bibliography


8. Figures

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Image from https://julianherzog.com/ under the creative commons licence.
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[Figure 24.2] 3D Digital Reconstruction of Top and Bottom Models of N.64 Kalychos Dedication
[Figure 25.] Unenhanced Image and 3D Photogrammetry Model of the N.84 “Casino Fount”
[Figure 25.1]  Publication Image and Depth Mapping of the N.84 “Casino Fount”
[Figure 26.] Unenhanced Image and Specular Enhancement of N.103 Artemidora Grave Marker
[Figure 26.1] Publication Image and 3D Photogrammetry Model of N.103 Artemidora Grave Marker
[Figure 26.2] Ambient Occlusion Filter of N.103 Artemidora Grave Marker
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