Preserving the Past for an Uncertain Future

Accessible, Low-Cost Methods for 3-D Data Creation, Processing, and Dissemination in Digital Cultural Heritage Preservation

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ABSTRACT

Digital heritage techniques such as photogrammetry and laser scanning are revolutionizing the way we can record, analyze, and disseminate 3D information about cultural heritage sites around the world. However, the expense and expertise required to conduct digital heritage work limits access to these exciting techniques, and furthers the divide between stakeholder groups to create artificial silos for "knowledge brokers" and "knowledge consumers." In this paper, we explore low-cost, simple technological, software, and Web3D solutions to build truly accessible digital heritage pipelines to democratize the field of digital heritage and return agency to previously disenfranchised stakeholder groups. Not only is this important from an equity standpoint, but it is required if we wish to digitally document as many heritage site as possible in the face of ever-increasing threats from climate change, social unrest, and natural disasters.

CCS CONCEPTS

• **Human-centered computing** → **Collaborative and social computing theory, concepts and paradigms**; **Collaborative content creation**; **Open source software**.

KEYWORDS

Digital Cultural Heritage, 3D scanning, 3D data, Virtual Reality

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1 INTRODUCTION

Heritage sites such as monuments and historical landmarks are fundamental components of cultural heritage, acting as standing symbols of the lives of those who previously resided in or alongside them [Mayes 2018; Otterstrom and Davis 2016]. They also serve as one of the few interpretive tools available to archaeologists and public historians for communicating the stories of past to the public in a visceral, experiential way [Marcal 2019; Mayes 2018]. A major challenge, however, is that heritage sites are often difficult and expensive to physically preserve, maintain, and make available for public access – especially compared to smaller scale material objects that can be conserved and displayed in museums. Heritage sites, on the other hand, largely must remain in-situ, enduring the elements and wear and tear from time and tourism, and are exposed to vandalism, natural disaster, and other external threats.

Over the last several decades, advancements in scanning technology and digital methodologies in archaeology and historic preservation have allowed for detailed electronic recordation of heritage sites that, in a sense, can help immortalize these monuments in the digital domain [Allen et al. 2003; Chee Wei et al. 2010; Jauregui 2018]. Despite these advances, there is still much that can be done to improve the field of digital preservation and the overall impact that it can make for public history, archaeology, and cultural heritage. The digital technologies currently in use in historic preservation are for the most part expensive (often costing above a hundred thousand US dollars) and often highly technical, limiting their use to only a select few and exacerbating the divide between heritage "knowledge brokers" and heritage "knowledge consumers" [Fortenberry 2019a,b]. This only further perpetuates the centuries-long dilemma of who "owns" the past, or, in this new case, who "owns" the digital representations of historical material [Shein 2018]. This debate further extends into who has the right to access digital heritage materials when these digital representations are made accessible over the internet via Web 3D technologies. We will return to this latter issue, which is one that does not have a single simple solution. The former remains an initial roadblock excluding many stakeholders who lack the means to acquire or technical know-how to employ the technologies considered "standard" in digital preservation. In fact, the inaccessibility of these technologies also limits the rate at which heritage sites can be digitally documented, so only a relatively small proportion of sites will be documented with these hard-to-get and hard-to-use tools. This begs the question of who gets to decide which sites are worthy of digital preservation, and which sites get passed over? Inevitably, smaller sites, sites that are in remote areas, or local sites that are important to a smaller set of stakeholders are the ones that are not being documented [Noonan 2007; Otterstrom and Davis 2016]. With the clock ticking on the global climate crisis, rising political unrest around the world, ever-increasing globalization and industrialization, and tourism levels growing at exponential rates, accessible technologies for digital heritage preservation are more necessary now than ever before. Cultural heritage sites – especially smaller, local sites – are surviving on borrowed time and with the current rate of digital preservation it won't be long before they are potentially lost forever.

In this paper we assemble and assess a set of accessible workflows for digital archaeology and cultural heritage preservation that can be conducted using tools and techniques that are financially, intellectually, and technologically approachable by a much wider group of stakeholders. We will showcase these workflows using the case study of a local heritage site in La Mesa, California. Our approach is meant to be flexible, offering a variety of reliable paths to achieving valid 3D digital models of heritage sites that can be deployed in a variety of preservation scenarios by a wide array of possible practitioners. Our explicit primary goal is to increase equity and inclusion in digital heritage documentation, not necessarily to derive the absolute highest precision in data collection. Indeed a focus on data precision and a general misconception of data precision and data accuracy instead of data validity in the sciences [Streiner and Norman 2006] can be seen as a major roadblock that professional practitioners (perhaps unconsciously) employ to "gate keep" the domain of 3D digital data acquisition – those without the "very best" tools are simply amateurs creating "useless" 3D models. We seek to subvert this position, and so we use only off-the-shelf tools, such as common camera formats and off-the-shelf LiDAR typically used in the autonomous vehicle industry and easily available software to process and display the 3D results. We stress that precision and technical accuracy are not an end-goal of digital heritage scanning in and of themselves, but rather, are only important in the context of a specific set of goals. For example, if a goal is to be able to monitor the structural displacement of a failing wall over time, the scanning method used must be able to differentiate movement or shape-change at a scale appropriate to the structure (i.e. the instrument must record measurements that are precise at the centimeter or millimeter scale, and must accurately and reliably record these measurements). If, however, the goal is simply to digitally represent the general shape and attributes of a structure to use as guide so that it could potentially be restored or reconstructed if damaged or destroyed at a later date, the overall precision and accuracy of the recordation technique can be much lower, and the technique does not necessarily have to be capable of the kind of reproducibility needed in the first scenario. Although the accuracy and precision of these different hypothetical 3D models are quite different, both of those hypothetical 3D models should be considered valid within their respective use-cases. Because of this, a secondary goal of our work is to provide a level of quality assessment for each potential low-cost workflow we assemble so that researchers can make informed decisions about where to invest time and money for a desired goal (especially compared to the very expensive "professional" level equipment currently in use by digital historic preservation practitioners). Finally, we will also be exploring the demand and benefits of making the end results produced from these workflows accessible to the general public through the use of 3D Web technologies. It is our hope that this entire pipeline – from scanning, to processing, to web display – will help to level the playing field in digital preservation, allowing students, scholars, or anyone with an interest in a particular subject to not only have access to interactive 3D models through a virtual environment, but also to create digital 3D data themselves that they can then share virtually as well. This can also empower traditionally disenfranchised stakeholders to tell their own stories through digital media [Comes et al. 2020; DeHass and Taitt 2018]. Allowing access to cultural heritage through an internet connection not only helps educate people about the material cultures and histories within their own and other communities around the world, but may also help peak interest in understanding why it is important that we preserve these sites for future generations [Comes et al. 2020; DeHass and Taitt 2018; O'Keeffe and Bergin 2015].

2 ACCESSIBILITY AND THE DIGITAL [R]EVOLUTION IN 3D HERITAGE SCANNING

Developing accessible methodologies for professional digital 3D scanning of heritage sites requires balancing affordability and ease-of-use with the quality of the results. To be successful, the scanning equipment must be affordable and the software must be easy to obtain and easy to use. The ideal workflow(s) will create 3D data at the level of quality needed for common historic preservation goals (if not for all usages within the field of digital historic preservation), but will be simple and affordable enough to be within the reach of so-called "citizen scientists." These latter are enthusiasts and local stakeholders that have typically been held at a distance by "professional" researchers, but who, with some training and collaboration, can help augment the small number of professional researchers in various fields [Bonney et al. 2009, 2014].. In the field of digital heritage, citizen science could be leveraged to create an engagement between hobbyists who enjoy history and scanning monuments and researchers and historic preservation practitioners to meet the ever-growing need to document heritage sites of all types, sizes, and perceived importance. This kind of partnership that may help to dismantle the ivory tower and build bridges between academia and the public, while simultaneously helping to achieve the documentation needed to help digitally preserve monuments – especially those that are under the radar of professional digital historic preservationists – that are deteriorating or becoming at risk at ever-faster rates.

2.1 Accessible hardware solutions

In this paper, we focus on two commonly used hardware solutions using to create 3D digital data: laser scanning and photogrammetry. Laser scanning has typically required equipment costing many thousands of dollars [Fortenberry 2019a,b], whereas photogrammetric techniques require only a digital camera and computer. However, recent shifts in the market for laser scanning technologies (specifically the increased demand for small, affordable laser scanning devices for use in the autonomous vehicle industry), have changed the price calculus for these devices. The ease of use, ubiquity, and "openness" of the hardware are other considerations that affect the accessibility of the hardware components of a 3D scanning pipeline. "Open" hardware is hardware where, at a minimum, the designs are made public with the intention to allow modification, service, or reproduction by anyone [Powell 2012]. Although a fully open 3D scanning hardware component would be an ideal anchor for an accessible pipeline, we take a more pragmatic approach and also consider "closed" hardware that is ubiquitous (and, thus, easy to attain) and/or of reasonable cost and complexity.

2.2 Accessible software solutions

Finding affordable scanning technologies is only half of the solution to improving the accessibility of 3D digital heritage preservation; the software needed to support these tools needs to be accessible as well. Closed-source processing and analysis software is often all but impossible to obtain by those outside the ivory towers of university departments, private companies, and individuals wealthy enough to pay the steep prices need to cover the license or subscription fees associated with them [Ducke 2012; Marwick et al. 2017]. On the other hand, "Free and Open Source Software," or FOSS, is software developed by community projects and made freely available to be utilized, updated, shared, and modified. Once highly technical (and therefore still somewhat inaccessible), there are now a wide variety of no-cost user-friendly alternatives to the closed-source programs that are just as capable of processing and producing quality results [Ducke 2015]. The potential accessibility of FOSS workflows lies within the definition of "open" itself in that "a piece of content or data is open if anyone is free to use, reuse, and redistribute it – subject only, at most, to the requirement to attribute and/or share-alike" [Lake 2012]. Although we prefer FOSS over closed-source software in principle, in reality there are some closed-source software that are made available at little or no cost that should not be ignored. These kinds of software are often referred to as "freemium," and although users do not pay for them with money, they may pay in some other currency such as their private data or through viewing ads or by being upsold through in-app purchases or for other services offered by the software provider such as hosting data in the cloud [Pujol 2010]. Some "freemiums" are more benign than others, however, and while we prefer true FOSS wherever possible, we err on the side of pragmatism to include accessible, effective, non-malicious "freemium" software solutions where it is useful to do so. In the same vein, we also consider "single price," "subscription," or "pay-per-use" closed-source software solutions when these costs are within reason (which we consider to be less than about $20 to complete at least one major project).

2.3 Accessible Web3D data sharing

The ability to store high-quality, interactive, 3D models of documented cultural heritage sites in online digital archives is imperative to accessible heritage preservation. Web accessibility can help aid in bridging the equity gap of who can engage in 3D documentation by lowering the locational barriers of contributing 3D data. This also increases access to 3D heritage information for education, research, and outreach. Although quality of life is at an all-time high in many parts of the world, a majority of the world population cannot afford the privilege of experiencing distant heritage sites in person and so the glimpse into the human experience that such opportunities provide is inequitably distributed. With Web3D digital experiences, historic preservation practitioners can virtually promote cultural heritage resources and increase the interaction of stakeholders cultural heritage assets [Comes et al. 2020]. Virtual Reality (VR) and Augmented Reality (AR) have become increasingly popular tools in fields like engineering, architecture and computer science, and are recently being increasingly employed in archaeology and heritage. If these technologies were more widely applied to cultural heritage and archaeology then data collected from places all over the world could be shared with a global audience (and although the digital divide still exists, it is getting smaller each year), which can help to ensure their importance to a wide variety of stakeholder groups [Little et al. 2018]. Not only this, but sharing heritage scans through an online format can help collaborative responses to catastrophic damages occurring to the physical site itself (i.e. destruction by means of natural disaster, climate change, and/or political unrest) [Lu 2020]. As with the scanning hardware and analysis software components of our accessible workflows, we preference free and open-source Web3D hosting software and services where possible, but pragmatically explore closed-source and pay services where simplicity, ubiquity, and/or practicality can increase accessibility.

3 ACCESSIBLE 3D DIGITAL HERITAGE SCANNING PIPELINES

Although there is a large range of potential pieces of hardware, software, and web technologies that could be included in an accessible 3D heritage scanning pipeline, we have narrowed our focus on the tools that follow. In the case study, we will offer example workflows showing how these components could be employed in accessible pipelines by preservation practitioners, including citizen scientists with minimal prior experience in 3D digital heritage work.

3.1 Accessible laser scanning

LiDAR (Light Detection and Ranging), or "laser scanning," is a cover-all term that is used in reference to different formats of technologies and methodologies that range from using satellites for mapping environmental conditions to close range 3D mapping of small-scale artifacts citeFernandez-Diaz2014. LiDAR is able to collect this type of data by utilizing laser pulses to acquire point coordinates along the surface of the object or area of interest. These points are captured in the form of an x, y, z point cloud that illustrates the shape of the object [Krusche et al. 2012]. The laser pulses may have several "returns," which are time-lagged reflections when a surface is partially obstructed, allowing the technique to "remove" vegetation from a scene. [Barrile et al. 2017; Fernandez-Diaz et al. 2014]. Until recently, access to LiDAR technologies has been limited due to the high price point and complexity of the technology [Fortenberry 2019a,b]. Terrestrial LiDAR scanning (TLS), also known as long-range laser scanning, is a form of 3D digital documentation in which a stationary, tripod-mounted laser scanner is used to document objects and areas [Barrile et al. 2017; Chee Wei et al. 2010]. This type of laser scanner is commonly used in fields of geoscience, architecture, surveying, construction and archaeology. Because of its static nature, TLS is able to collect more accurate captures than mobile laser scanning [O'Neill 2020]. However, traditional TLS is exceptionally expensive and complex. A professional terrestrial laser scanner used in digital architectural scanning can cost up to $150,000 USD [Fortenberry 2019a]. Cost is dependent on the range, speed and features of each scanner and often, each unit is bundled with accompanying proprietary software to process data collected [O'Neill 2020]. An alternative to TLS is mobile laser scanning which integrates the same laser technology but allows the user to collect data while in motion. In addition to being carried around by the user, common modes of operation for mobile scanning include the apparatus being mounted to a moving vehicle such as a car or aerial drone [O'Neill 2020]. Drones, in turn, provide another obstacle to the accessibility of equipment due to the high price point and limitations on who is permitted to operate the vehicle. In addition to costing upwards of $10,000 to $20,000 USD for a drone capable of carrying a LiDAR payload, in the United States and many other countries, a specialized license and/or permit is also required for users to operate a drone in a professional context. Because of this lack of accessibility, LiDAR technology has primarily been used by a select few "expert" stakeholders who have access to the funds and knowledge needed to integrate the method into research and preservation practices. We aim to subvert this by modifying an "off-the-shelf" Livox Avia LiDAR unit that is designed for flexible use in a variety of situations, including in the autonomous vehicle industry. Although not fully "open," Livox hardware is made to be semi-"hackable" so that users can create customized rigs or harnesses. Our laser scanning set up, including the LiDAR unit, battery, connection cables, and tripod, cost less than $2,000 USD, and easily connects to a standard laptop via ethernet connection for data collection using the open-source software supplied by the manufacturer.

Because of our choice of Livox hardware, we also use the free software acquisition platform provided by the company, "Livox Viewer". Livox Viewer (https://www.livoxtech.com/downloads) is free software for Linux and Windows provided by Livox to control and configure Livox LiDAR scanners, allowing for rudimentary 3D data acquisition and export to accessible .CSV or .LAS pointcloud formats. Although more robust FOSS Livox scanning solutions can be configured using the open-source Livox SDK or with the open-source "Robot Operating System" package, we chose to use Livox Viewer because it is very easy to use and allows basic single-viewpoint 3D scanning with any Livox LiDAR scanner. Exported pointcloud data needs to be edited in a different program, such as CloudCompare (see below). Livox Viewer has a simple learning curve.

Figure 1: A Livox Avia LiDAR scanner, adapted for digital heritage scanning using easy to find off-the-shelf components (photo credit: S. Benchekroun).

3.2 Accessible photogrammetry

Wolf et al. [2014] define photogrammetry as "the art, science, and technology of obtaining reliable [3D] information about physical objects and the environment through the processes of recording, measuring, and interpreting photographic images." [Wolf et al. 2014]. This method is primarily utilized by researchers to record 3D measurements of objects, landscapes, and buildings. Photogrammetric techniques are often favored over laser scanning methods for digital 3D data creation because they can be more cost effective, requiring little more than a camera and computer [Green et al. 2014; Yilmaz et al. 2008]. Multi-image photogrammetry, or Structure from Motion (SfM), refers to the process of taking an overlapping series of clear, high resolution photographs of the desired site or object and then using recent developments in computer vision technology to create a 3D model from the 2D images [Green et al. 2014; James and Robson 2012]. This workflow consists of capturing a sequence of overlapping images of a selected object or area, all taken from the same distance, and using newly developed algorithms to discover matching points across 3 or more images that can be triangulated to back-compute the camera positions and thereby create a unified 3D pointcloud model of the object or location. The processing stage is time-intensive and requires a computer with a capable CPU and decent RAM (at least 8GB or more), although certain SfM algorithms can take advantage of the GPU on CUDA-enabled systems to increase processing speeds (e.g., [Zheng et al. 2017]). Because the input data are photographs, SfM techniques cannot "remove" vegetation coverage as can be done with LiDAR, and resultant 3D models are prone to gaps where multiple image coverage is not possible or where points cannot be positively matched. Despite these issues, SfM is perhaps the most accessible method to gather 3D data [DeHass and Taitt 2018; Fortenberry 2019b]. We explore here the efficacy of three different common camera systems for the SfM 3D data creation pipeline. The first system is a professional-grade Interchangeable Lens Camera (ILC) with a high-quality lens that can capture very high-quality images. The total cost of this kind of camera and lens is in the $1000 to $3000 USD range. The second system is a consumer-grade "action camera" that can be mounted on a boom pole for angles of view that mimic a low-flying aerial drone. The cost of this camera system is around $100 to $500 USD. The final system is the built-in camera on a smartphone. Modern smartphones have very good camera modules, and the ubiquity of smartphones in daily life means that they are the ultimate accessible photographic tool. Although new smartphones can cost anywhere between $100 and $2000, we will use an older-model iPhone making this system essentially "free" in that no additional photographic equipment would need to be purchased by most people. ILC or action cameras require the used of a computer-based photogrammetry software workflow, and we preference "Open Drone Map" (ODM) – in particular the GUI-based "WebODM" branch of ODM – as the most accessible computer-based solution to producing usable 3D digital data via the SfM technique. Open Drone Map (https://www.opendronemap.org/) is a FOSS photogrammetry suite for Linux, MacOS, and Windows, accessible as a scriptable command-line interface or as a user-friendly graphical interface via a web browser, complete with visualization, storage, and rudimentary data manipulation and analysis functionality. The software exports pointclouds and textured meshes (optionally georeferenced if gcp or GPS data was included) in common accessible formats (.LAS, .PLY, and .OBJ among others). It is free, although there is an affordable single-price branch that offers a simple one-step installer and installation support. Open Drone Map has an easy to moderate learning curve, and there is ample community-based support for the software, making it a good choice for a novice user. A potential downside of ODM (and WebODM), is that it is geared towards imagery captured with an aerial drone, and is perhaps better-suited for 3D digital landscape reconstruction than 3D monument reconstruction from images capture only on the ground. An alternative GUI-based FOSS SfM solution is Meshroom (https://alicevision.org/), and an alternative command-lined FOSS SfM solution is MVE (https://github.com/simonfuhrmann/mve). Both can produce dense textured mesh reconstruction, and run on Linux, Windows, or MacOS. We think that WebODM is easier to use than either of these alternatives, but these programs are both relatively simple to install and run for those with moderate to advanced computer experience. For the iPhone hardware, Trnio (https://www.trnio.com/) offers an accessible app-based 3D scanning photogrammetry solution. It offers a very low-cost "single price" pathway with limitations on data precision, and soon will offer a higher-quality "subscription" and "pay-per-use" pathways. Currently, Trnio is considered best for small to medium sized objects, such as statues, small edifices, or smaller monuments. The forthcoming "Plus" version purports to be able to complete higher quality scans and scans of larger objects, and will be able to utilize the built-in LiDAR on the iPhone 12 and newer. Rendered 3D models can be exported in the .OBJ format, or uploaded directly to Sketchfab. Trnio has a very simple learning curve and operates completely on a ubiquitous device, making it perhaps the most accessible 3D photogrammetry solution we know of.

3.3 Accessible 3D data editing and analysis

Whether generated via laser scanning or photogrammetry, the raw 3D digital scan data will need to be edited before it is ready for analysis and/or sharing. At a minimum, outlier points or vertices need to be trimmed, multipart scans need to be aligned and joined, and the pointcloud or mesh needs to be assessed for quality in relation to the intended purpose of the scan. Optionally, pointclouds can be converted into meshes, and pointclouds or meshes can be smoothed, decimated, and/or textured. The data may also need exporting or conversion to a different file format, depending on the final archival or Web3D hosting requirements. We prefer CloudCompare (https://www.danielgm.net/cc/) as the most accessible editing and analysis software solution. CloudCompare is FOSS and runs on Linux, MacOS, and Windows, and has a moderate learning curve. A strength of CloudCompare is in registration, alignment, and comparison of pointclouds. CloudCompare can work with meshes – for example, mesh structures can be interpolated from pointclouds – but is more focused on pointcloud analysis. CloudCompare can import and export a variety fo common pointcloud and mesh formats, including .LAS, .OBJ, and .PLY files. An external tool, such as Model Converter (https://modelconverter.com/) or Blender (https://www.blender.org/), is needed to export to Web3D compatible formats (.glTF or .GLB). A popular alternative to CloudCompare is Meshlab (https://www.meshlab.net/), which is another FOSS for Linux, MacOS, and Windows capable of editing and analyzing pointcloud and mesh data. Meshlab, in contrast to CloudCompare, has a focus on meshes, but we think it has a much steeper learning curve. Meshlab provides a detailed set of tools for editing, rendering, texturing, cleaning, inspecting and converting meshes, making it more powerful than CloudCompare at the expense of reducing usability. A third alternative is Blender, which we have already mentioned is the only FOSS mesh editor that can export Web3D-friendly .glTF and .GLB files directly. Blender's main focus is in 3D animation and compositing and it runs on Linux, MacOS, and Windows. Although aimed more at the creative arts, Blender has a suite of mesh editing tools and plugins that can be used to edit 3D heritage data. Because of the wide array of useage scenarios within Blender, it has a more difficult learning curve than CloudCompare.

3.4 Accessible Web3D and data sharing

We have found Sketchfab (https://sketchfab.com/) to be the most accessible solution for hosting and sharing interactive 3D digital heritage data. Sketchfab is a web-based "freemium" or subscription-based 3D and AR viewer and data hosting platform. Sketchfab's business model also allows buying and selling of 3D data with commissions. Data can be discovered in multiple ways on the platform, and users can share links or obtain html code to embed a 3D viewer in any website. All data uploaded to the site must be licensed, and permissive Creative Commons licenses are available so data sets can be provided for free download and reuse with minimal restrictions. SketchFab has rapidly become one of, if not the, most popular hub for sharing 3D models on the web, including 3D models of heritage sites and other monuments. It can import a wide variety of 3D data formats, including .OBJ, .PLY, and .LAS, and can export to Web3D-friendly formats such as .glTF for direct rehosting on a different platform. Freemium accounts are limited to file sizes of 100mb, and 10 uploads per month. Sketchfab has an easy to moderate learning curve. OpenHeritage3d (https://openheritage3d.org/) is a more open alternative "all in one" hosting solution to Sketchfab that is dedicated solely to interactive viewing and hosting of open 3D heritage data. The platform is provided by the Open Heritage Alliance, which aims to digitally curate the world's heritage sites in an openly accessible format. Anyone can access and download the data hosted on the platform, and they accept data uploads from reputable institutions by request. The centralized, yet specialized nature of this repository makes it an attractive option for hosting 3D heritage data for sharing, but this is somewhat offset by the (necessary) "gatekeeping" aspect of the upload process. OpenHeritage3D has an easy learning curve to use, but we do not know how difficult it would be to upload data for hosting. That being said, however, the specialized digital heritage focus of OpenHeritage3d provides an advantage for discoverability of shared 3D digital heritage data that is uploaded to the platform. A final alternative we consider is to host the digital data files in a persistent and open online archive, such as GitHub, and to use javascript tools to present interactive Web3D presentations embedded into a static website. There are several javascript tools available for custom Web3D presenters, but we think the simplest, and therefore the most accessible tool is <model-viewer> (https://modelviewer.dev/). <model-viewer> is a FOSS javascript tool built on Three.js that is a simple interactive Web3D viewer that can be embedded in any website in any modern webbrowser. The tool requires a .glTF or .GLB data source, and can create static views, interactive views, or AR views of the 3D data. It can be easily implemented with basic html because the javascript elements can be imported directly from a provided unpkg server. It has a powerful API that allows for fine control of styling and interaction if desired, but a basic embedded Web3D presenter can be inserted into a static website as simply as copying and pasting example code from the <model-viewer> website, and then editing the URL of the datasource. Because of this, we consider <model-viewer> to have a simple to moderate learning curve. A more powerful Web3D presentation tool that is also based on Three.js is Potree (https://github.com/potree/potree/). Potree is optimized for interactive viewing of very large 3D point-clouds. It offers embedded analysis, styling, and measuring tools, but is much more complex to set up and install on a website. All 3D data need to be converted to a special potree format via and included converter tool. A third alternative is 3D Heritage Online Presenter (3DHOP: https://www.3dhop.net/). 3DHOP is a FOSS web framework for embedding a viewer for 3D heritage models in any website in any modern webbrowser. The tool runs on Windows, Mac OS, and Linux, and does require a minimal knowledge of html and javascript. One advantage of 3DHOP is that it can directly render small (<1mb) single-resolution 3D data files in the .PLY format. Larger 3D models must, however, be converted to the multiresultion NEXUS (.nxs or .nxz) format via a converter tool that currently only works in the Windows operating system. 3DHOP is more difficult to use than <model-viewer>, but perhaps less difficult than Potree.

3.5 Accessible 3D Heritage Pipelines

The hardware, software, and web tools detailed in sections 3.1 through 3.4 should be thought of as components that can be flexibly assembled into "pipelines" for 3D heritage scanning, editing, analysis, and web sharing workflows. Flexibility is a key component to accessibility because it allows the user to choose tools that align with their existing skill set, equipment, budget, and software. In section 4 below, we provide a practical example pipelines that we employed in a real-life case study. While it is possible pipelines to assemble a completely "open source" pipeline from hardware to web service, we offer pragmatic suggestions for increasing openness where possible or desired, but also note where closed-source alternatives can be substituted for maximum flexibility.

4 CASE STUDY: THE HENRY A. MCKINNEY HOUSE

The McKinney house was built in 1908 by Reverend Henry A. McKinney, and is a staple of local history in the small town of La Mesa, California [Newland 2010]. In 1975 the property was sold to The La Mesa Historical Society (a non-profit organization) and in 1980 it was officially converted into a museum with the exterior, interior, and furnishings kept in the same order they had been decades prior. The house was also the very first building designated as a local historical landmark by the city of La Mesa [City of La Mesa 2021]. The McKinney house museum operated by the La Mesa Historical Society (LMHS) allows visitors to tour the house to gain a glimpse into the past of this small California town, but, due to the realities of funding and staffing, can only be open for a few hours on Saturdays [La Mesa Historical Society 2021]. The museum has been closed for the duration of the ongoing COVID-19 pandemic, further limiting public access to this important local landmark. Further, the McKinney house is about a block away from the Randall Lamb design studio – another official local historical landmark – that was burned down by intentional arson during the riots following a Black Lives Matter protests on May, 30th 2020 [Newland 2020]. If the riot had made its way closer to the McKinney house there is no assurance that it would not have also been a target for damage or destruction. This only further exemplifies the exigency for accessible digital preservation.

5 METHODS

We used three accessible 3D scanning pipelines to digitally document the McKinney House: 1) laser scanning with the Livox Avia, 2) computer-based SfM with images acquired using an ILC and processed with WebODM, and 3) an iPhone and the Trnio app. All pipelines were conducted by the same practitioner, who had a minimal level of experience with 3D scanning prior to conducting this work. The practitioner was given some basic instructions on how to operate the hardware, and relied on any available documentation and tutorials, including community-created videos and articles, to learn the software routines required to create a finished 3D model from the scan data. Qualitative information about the difficulties, accessibility, and quality of each pipeline were noted during the field scanning and follow up analysis. All acquired 3D data were brought into CloudCompare for processing and analysis. The Livox Avia data were acquired from four viewpoints, which were aligned and

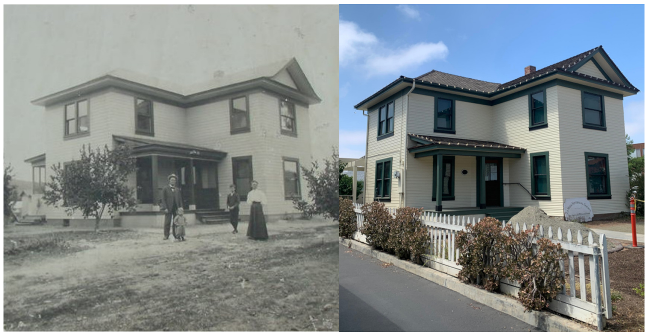

Figure 2: Left: Historical photograph of the McKinney house ca. 1910 (image courtesy of the La Mesa Historical Society). Right: Recent 2021 photograph of the McKinney house from roughly the same angle (photo credit: S. Benchekroun).

merged in CloudCompare. The ILC photogrammetry was acquired in two transects, which produced two pointclouds in WebODM that were aligned and merged in CloudCompare. The Trnio app provided a single pointcloud. For all three pointclouds, extraneous points were removed and the cloud was scaled and oriented to an aribitrary meter grid with a datum set to the southwest corner of the house. We gathered basic statistics about the geometry of each cloud, including the total number of points, the surface roughness, the surface variance, the mean surface curvature, and the mean point density. After analysis, if necessary, the pointclouds were subsampled to produce a smaller-sized file for upload to a Web3D sharing platform. We uploaded the pointclouds to both Sketchfab and to GitHub where we used <model-viewer> to host interactive Web3D visualizations of the three datasets on a GitHub "sites" page.

6 RESULTS

Still captures of the three resulting 3D pointclouds colored by surface roughness are shown in Figure 3, and interactive Web3D viewers for eachpointcloud can be viewed at https://isaacullah.github.io/Web3D_pipelines/. Qualitatively, the Livox scan appears to contain the most detail, and renders the sharpest and densest looking pointcloud. The Trnio pointcloud is the least sharp, detailed, and dense, and the WebODM pointcloud is moderately sharper, denser, and detailed than the Trnio cloud. Our practitioner noted that the Livox workflow, once established, was fairly intuitive, as all it required was moving the tripod from one corner of the lot to another, and conducting a short 5-second scan. The four clouds that resulted from this pipeline did need to be trimmed, aligned, and merged in CloudCompare, however, but the density and level of detail made the process of matching alignment points between the clouds relatively easy. The field scan using the Trnio app was the next simplest, as it only required for the app to be launched, and then the practioner traversed the lot while keeping the camera of the iPhone pointed at the house. Helpful on screen tips let the practitioner know to speed up or slow down. Unfortunately, the rendered 3D model contained many artifacts that needed removal, so the follow up process in CloudCompare was not as simple as the field scanning was. The practitioner encountered the most difficulty with the ILC photogrammetry pipeline. Part of this was confusion on how best to gather photographs for SfM, including the number of photographs and the amount of overlap to include. The practitioner gathered 21 photographs in two roughly linear transects running roughly southeast to northwest and southwest to northeast, covering views of the southern, western, and northern sides of the house. Access along the eastern side of the house was hampered because of the proximity to the property line and fence. WebODM requires at least 85% overlap between photographs to create the highest quality 3D pointcloud, and the image set our practioner gathered did not meet these requirements. The two pointclouds that derived from processing each image transect, respectively, also did not have enough overlap for an automatic alignment using the point matching tool in CloudCompare, so the two pointclouds had to be aligned and merged by eye, which made the follow up process much more complicated. All methods had difficulty gathering sufficient points to fully reconstruct the roof structure of the house, and the limited access along the eastern elevation meant that this side of the house was the least dense and detailed portion of pointcloud from each of the three pipelines.

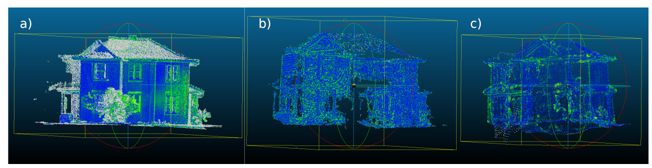

Figure 3: Pointclouds derived from three accessible 3D scanning pipelines, colored by surface roughness. Color scales are relative, and green denotes rougher areas within each model. a) Pointcloud derived from the Livox Avia laser scanner. b) Pointcloud derived from WebODM and imagery caputured with an ILC. c) Pointcloud derived from the Trnio app on an iPhone. Each scene is roughly aligned to the same view.

We used CloudCompare to generate some basic statistics about the geometry of each of the 3D pointclouds (Table 1). The laser-scanning pipeline produced the densest, smoothest pointcloud, with almost 3 million points. The ILC and WebODM photogrammetry pipeline produced a pointcloud that was almost as smooth as the laser-scanned cloud, but which was significantly less dense at less than 300,000 points. The Trnio and iPhone photogrammetry pipeline produced the least dense pointcloud at less than 50,000 points, and was significnatly rougher than the other two clouds. The .LAS files for the three clouds are 208.5mb in size for the laser-scanning pipeline, 11.7mb for the ILC and WebODM pipeline, and 0.976mb for the Trnio and iPhone pipeline.

7 DISCUSSION

Our practioner was able to produce pointclouds through all three of the methods we tested. Surprisingly, however, the higher-quality photogrammetry workflow proved to be the most difficult pipeline for the practioner to employ. The pointcloud created with this pipeline was qualitatively and quantitatively better than that of the simpler Trnio and iPhone pipeline, but not as good as that produced using the Livox laser scanner. With a more appropriate set

Table 1: Statistics describing basic geometric properties of each 3D pointcloud.

Model Name	Total # of points	Mean Surface Roughness	Mean # of Neighbors	Mean Surface Density
Livox Avia	2817762	0.00032 +/- 0.0028	137.819 +/-229.839	41673.9 +/-69499.1
WebODM and ILC	278343	0.0041 +/-0.0034	45.0817 +/-26.5447	7136.74 +/-4202.21
Trnio and iPhone	48786	0.0166 +/-0.0154	17.0212 +/-7.533	125.88 +/-55.7101

of imagery, however, we believe that the WebODM pipeline output could be significantly improved. A major benefit of the photogrammetry pipelines is that they provide texture for the pointclouds (and resulting meshes), which can allow a photorealistic 3D model to be rendered if desired. The Livox laser-scanner produced the densest, most detailed pointcloud, and was surprisingly easy for the practitioner to use. It produced the largest file size, however, meaning that a subsampled cloud had to be created for upload to the free-tier of Sketchfab. Of the three pipelines, we have confidence that the Livox laser-scanning pipeline and the ILC and WebODM pipeline could produce datasets of high-enough quality to satisfy basic heritage documentation needs, and could provide adequate supplemental digital scan data for a basic documentation project, for example using the United States Department of the Interior's "HABS" documentation format [US Department of the Interior 2008]. The Trnio pipeline may be more appropriate for smaller monuments, where we expect it to be able to produce better datasets. The future improvements to Trnio may increase the quality of the output for larger monuments, however, but at this time, we think Trnion is mostly useful as a very simple, very affordable pipeline for producing 3D models meant for casual use, perhaps, for example, in an online museum display, where data accuracy is less important. A weakness of all three pipelines as employed by our practitioner was in obtaining data for the roof structure, and for the eastern elevation of the house where access was limited. This could be mitigated using a taller tripod or boom pole, or by acquiring scans or photos from further away. Our experience hosting these data in an interactive Web3D accessible format has been generally positive as well. By far, we feel that the free tier of Sketchfab is the most accessible method to achieve this. Only the 100mb file-size limitation encumbered the Sketchfab experience, although this only mattered for the laser-scanned pointcloud. It was very simple to upload our models and to copy and paste the embed code into our webpage document. Our choice of GitHub sites for the webhost may not be the most accessible (a WYSIWYG service like Google Sites or Squarespace might be), but we think the copy and paste process is simple enough in most any webpage building context. <model-viewer> was only marginally more complicated, however, and we like the freedom it provides to host our data in any way we like. This is better from an archival and accessibility perspective because we can choose to host our data with services that may be better aligned with the goals of the open science movement [Marwick et al. 2017]. We think the extra complexity of this may be worth it if long-term access to the data is a primary objective for the scanning project.

8 CONCLUSIONS

We have provided a flexible, multi-pronged approach for low-cost, accessible creation, processing, and web-hosting of digital heritage materials. We exemplified this with a case study in partnership with the LMHS by showcasing the outcomes of different 3D scanning pipelines of varying complexity and accessibility for digital recordation of the McKinney House. Importantly, we showed that a relatively inexperienced practitioner could successfully produce high quality 3D data using our pipelines, and share these via and interactive online Web3D platform. Our long term goal is to continue the partnership with the La Mesa Historical Society to share the Web3D data we create with visitors and patrons interested in experiencing the site but lacking the means or ability to be there in person. The City of La Mesa currently recognizes around 40 local historical landmarks [City of La Mesa 2021], including the personal residence of one of the authors. These local landmarks are important to the residents of the City of La Mesa, but are likely of lower importance at the state or national level, and would likely never receive the attention of professional digital preservation practitioners. The accessible 3D digital recordation pipelines we are producing feasibly can help the LMHS and other local stakeholders conduct future scans of their own. In a proximate next research step, we will compare the output of our accessible 3D scanning pipelines with traditional professional quality 3D scans. The McKinney house was scanned using a professional TLS laser scanner in 2018 by ChronoPoints (a component of the SENSEable Design Lab at the University of Central Florida's IST, School of Modeling, Simulation & Training), who have made their pointcloud publicly viewable through their website [ChronoPoints 2021], and who have recently agreed to send us the full pointcloud dataset. This will provide an excellent opportunity to compare the quality of the results obtained through our accessible 3D scanning pipelines to that of a professional laser scanner. We hope that our accessible piplelines will produce 3D data of comparable, if not equal, quality to those previously collected with expensive, exclusionary, high-end equipment. In the long term, we believe that these methodologies will not only benefit the fields of digital archaeology, historic preservation, and cultural heritage management on a practical level, but will also expand access, control, and agency over the creation and dissemination of digital heritage assets to those who are directly connected to the heritage sites as it should always have been. Finally, we believe these methods will allow for the public to get more involved in both the documentation and visualizations of cultural heritage, which we hope will expand both interest in, and care of, our shared material past.

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REFERENCES

P.K. Allen, I. Stamos, A. Troccoli, B. Smith, M. Leordeanu, and Y.C. Hsu. 2003. 3D modeling of historic sites using range and image data. In *2003 IEEE International Conference on Robotics and Automation (Cat. No.03CH37422)*, Vol. 1. 145–150. https://doi.org/10.1109/ROBOT.2003.1241587

V. Barrile, G. Bilotta, G. M. Meduri, D. De Carlo, and A. Nunnari. 2017. LASER SCANNER TECHNOLOGY, GROUND-PENETRATING RADAR AND AUGMENTED REALITY FOR THE SURVEY AND RECOVERY OF ARTISTIC, ARCHAEOLOGICAL AND CULTURAL HERITAGE. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences* IV-4/W4 (2017), 123–127. https://doi.org/10.5194/isprs-annals-IV-4-W4-123-2017

Rick Bonney, Caren B. Cooper, Janis Dickinson, Steve Kelling, Tina Phillips, Kenneth V. Rosenberg, and Jennifer Shirk. 2009. Citizen Science: A Developing Tool for Expanding Science Knowledge and Scientific Literacy. *BioScience* 59, 11 (12 2009), 977–984. https://doi.org/10.1525/bio.2009.59.11.9

Rick Bonney, Jennifer L. Shirk, Tina B. Phillips, Andrea Wiggins, Heidi L. Ballard, Abraham J. Miller-Rushing, and Julia K. Parrish. 2014. Next Steps for Citizen Science. *Science* 343, 6178 (2014), 1436–1437. https://doi.org/10.1126/science.1251554

Ong Chee Wei, Cheong Siew Chin, Zulkepli Majid, and Halim Setan. 2010. 3D documentation and preservation of historical monument using terrestrial laser scanning. *Geoinformation Science Journal* 10, 1 (2010), 73–90.

ChronoPoints. 2021. McKinney House – La Mesa. https://chronopoints.eecs.ucf.edu/portfolio_page/mckinney-house/

City of La Mesa 2021. Historic Landmarks. https://www.cityoflamesa.us/765/Historic-Landmarks

Radu Comes, Călin Neamțu, Zsolt Levente Buna, Ștefan Bodi, Daniela Popescu, Vasile Tompa, Rareș Ghinea, and Liliana Mateescu-Suciu. 2020. Enhancing Accessibility to Cultural Heritage Through Digital Content and Virtual Reality: A Case Study of the Sarmizegetusa Regia UNESCO Site. *Journal of Ancient History and Archaeology* 7, 3 (2020). http://jaha.org.ro/index.php/JAHA/article/view/561

Medeia Krisztina Csoba DeHass and Alexandra Taitt. 2018. 3D Technology in Collaborative Heritage Preservation. *Museum Anthropology Review* 12, 2 (2018), 120–152. https://doi.org/10.14434/mar.v12i2.22428

Benjamin Ducke. 2012. Natives of a connected world: free and open source software in archaeology. *World Archaeology* 44, 4 (2012), 571–579. https://doi.org/10.1080/00438243.2012.743259

Benjamin Ducke. 2015. *7 Free and Open Source Software in Commercial and Academic Archaeology.* De Gruyter Open Poland, 92–110. https://doi.org/doi:10.1515/9783110440171-008

Juan Carlos Fernandez-Diaz, William E. Carter, Ramesh L. Shrestha, and Craig L. Glennie. 2014. Now You See It... Now You Don't: Understanding Airborne Mapping LiDAR Collection and Data Product Generation for Archaeological Research in Mesoamerica. *Remote Sensing* 6, 10 (2014), 9951–10001. https://doi.org/10.3390/rs6109951

Brent Fortenberry. 2019a. Digital Documentation in Historic Preservation Education and Research: Prospects and Perils. *Preservation Education & Research* 11 (2019), 81–116. https://www.jstor.org/stable/10.5749/preseducrese.11.2019.0081

Brent Fortenberry. 2019b. Digital Documentation in Vernacular Architecture Studies. *Buildings & Landscapes: Journal of the Vernacular Architecture Forum* 26, 2 (2019), 98–114.

Susie Green, Andrew Bevan, and Michael Shapland. 2014. A comparative assessment of structure from motion methods for archaeological research. *Journal of Archaeological Science* 46 (2014), 173–181. https://doi.org/10.1016/j.jas.2014.02.030

M. R. James and S. Robson. 2012. The accuracy of photo-based structure-from-motion DEMs. In *EGU General Assembly Conference Abstracts (EGU General Assembly Conference Abstracts)*. 4550.

Andre Jauregui. 2018. *Heritage Reproduction in the Age of High-Resolution Scanning: A Critical Evaluation of Digital Infilling Methods for Historic Preservation.* Master's thesis. Columbia University.

K. Krusche, P. Turner, and C.J. Sweet. 2012. History in 3D: New Virtualization Techniques for Innovative Architectural and Archeological Scholarship and Education. In *Archaeology in the Digital Era: Papers from the 40th Annual Conference of Computer Applications and Quantitative Methods in Archaeology (CAA)*, E. Graeme (Ed.). Amsterdam University Press.

La Mesa Historical Society 2021. La Mesa Historical Society. https://lamesahistory.com/about-us/

Mark Lake. 2012. Open archaeology. *World Archaeology* 44, 4 (2012), 471–478. https://doi.org/10.1080/00438243.2012.748521

Chris Little, Dale Patterson, Brent Moyle, and Alexandra Bec. 2018. Every Footprint Tells a Story: 3D Scanning of Heritage Artifacts as an Interactive Experience. In *Proceedings of the Australasian Computer Science Week Multiconference* (Brisband, Queensland, Australia) *(ACSW '18)*. Association for Computing Machinery, New York, NY, USA, Article 38, 8 pages. https://doi.org/10.1145/3167918.3167974

C. Lu. 2020. *Digital Restoration Proposal for Notre Dame statues.* Master's thesis. University of Dublin.

Helia Marcal. 2019. Public Engagement Towards Sustainable Heritage Preservation. *Protection of Cultural Heritage* 8 (December 2019), 185–210. https://doi.org/10.35784/odk.1084

B. Marwick, J. d'Alpoim Guedes, C. M. Barton, L. A. Bates, M. Baxter, A. Bevan, E. A. Bollwerk, R. K. Bocinsky, T. Brughmans, A. K. Carter, C. Conrad, D. A. Contreras, S. Costa, E. R. Crema, A. Daggett, B. Davies, B. L. Drake, T. S. Dye, P. France, R. Fullagar, D. Giusti, S. Graham, M. D. Harris, J. Hawks, S. Heath, D. Huffer, E. C. Kansa, S. W. Kansa, M. E. Madsen, J. Melcher, J. Negre, F. D. Neiman, R. Opitz, D. C. Orton, P. Przstupa, M. Raviele, J. Riel-Savatore, P. Riris, I. Romanowska, J. Smith, N. Strupler, I. I. Ullah, H. G. Van Vlack, N. VanValkenburgh, E. C. Watrall, C. Webster, J. Wells, J. Winters, , and C. D. Wren. 2017. Open science in archaeology. *SAA Archaeological Record* 17, 4 (2017), 8–14.

Thompson M. Mayes. 2018. *Why old places matter: How historic places affect our identity and well-being.* Rowman & Littlefield.

James D. Newland. 2010. *La Mesa.* Arcadia Publishing.

James D. Newland. 2020. A Small Town's Interconnected Historic Landscape: The History of the Three Buildings Lost on May 30th Reveal Our Small Town's Intertwined Commercial Past. Lookout Avenue Newsletter, Mesa Historical Society. , 12-23 pages.

Douglas S. Noonan. 2007. Finding an Impact of Preservation Policies: Price Effects of Historic Landmarks on Attached Homes in Chicago, 1990-1999. *Economic Development Quarterly* 21, 1 (2007), 17–33. https://doi.org/10.1177/0891242406296326

Shawn O'Keeffe and Danu Bergin. 2015. OpenBIM Framework for a Collaborative Historic Preservation System. *International Journal of 3-D Information Modeling (IJ3DIM) 5(4)* 5.

Benedict O'Neill. 2020. Terrestrial laser scanners (long-range scanning): A complete guide. https://www.aniwaa.com/buyers-guide/3d-scanners/terrestrial-laser-scanners-long-range/

Samuel M. Otterstrom and James A. Davis. 2016. The Uneven Landscape of California's Historical Landmarks. *Geographical Review* 106, 1 (2016), 28–53. https://doi.org/10.1111/j.1931-0846.2015.12133.x

Alison Powell. 2012. Democratizing production through open source knowledge: from open software to open hardware. *Media, Culture & Society* 34, 6 (2012), 691–708. https://doi.org/10.1177/0163443712449497

Nicolas Pujol. 2010. Freemium: Attributes of an Emerging Business Model. Social Science Research Network. https://dx.doi.org/10.2139/ssrn.1718663

Esther Shein. 2018. Who Owns 3D Scans of Historic Sites? *Commun. ACM* 62, 1 (dec 2018), 15–17. https://doi.org/10.1145/3290410

D. L. Streiner and G. R. Norman. 2006. "Precision" and "Accuracy": Two Terms That Are Neither. *Journal of Clinical Epidemiology* 59, 4 (April 2006), 327–330. https://doi.org/10.1016/j.jclinepi.2005.09.005

US Department of the Interior 2008. HABS guidelines: Recording Historic Structures and Sites with HABS Measured Drawings.

Paul R. Wolf, Bon A. Dewitt, and Benjamin E. Wilkinson. 2014. *Elements of Photogrammetry with Applications in GIS (Fourth Edition).* McGraw Hill.

H.M. Yilmaz, M. Yakar, and F. Yildiz. 2008. Documentation of historical caravansaries by digital close range photogrammetry. *Automation in Construction* 17, 4 (2008), 489–498. https://doi.org/10.1016/j.autcon.2007.09.003

Maoteng Zheng, Shunping Zhou, Xiaodong Xiong, and Junfeng Zhu. 2017. A New GPU Bundle Adjustment Method for Large-Scale Data. *Photogrammetric Engineering & Remote Sensing* 83, 9 (September 2017), 633–641. https://doi.org/10.14358/PERS.83.9.633