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REVIEW **Open Access**

Standardization of digitized heritage: a review of implementations of 3D in cultural heritage

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Abstract

The value of three-dimensional virtual objects are proven in a great variety of applications; their flexibility allowing for a substantial amount of utilization purposes. In cultural heritage this has been used for many years already, and the amount of users continue to grow as acquisition methods and implementations are becoming more approachable. Nonetheless, there are still many apparent issues with making use of all the possible benefits of 3D data in the field, varying from lack of knowledge, infrastructure, or coherent workflows. This review aims to underline the current limitations in implementing 3D workflows for various cultural heritage purposes. 45 projects and institutions are reviewed, along with the most prominent guidelines for workflows and ways of implementing the 3D data on the web. We also cover how each project manage and make their data accessible to the public. Prominent and recurring issues with standardization, interoperability, and implementation is highlighted and scrutinized. The review is concluded with a discussion on the current utilization's of 3D data for cultural heritage purposes, along with suggestions for future developments.

Keywords 3D Data, Cultural heritage, Digitization, Guidelines, Standardization

Introduction

Three-dimensional capture of an objects shape and appearance has many applied and theorized uses, and current technology has made the acquisition of such data more approachable for both experts and novices than what it used to be. By using different non-contact techniques one is able to capture the coordinates of different parts of an object in a 3D space, which can be used to visualize the object in several different ways. This approach is applicable for any object size as long as one is able to collect images of good quality or maintain line-of-sight with the object during acquisition, and is extensively researched and applied to the medical field [1], construction [2], and indeed cultural heritage (CH). This review creates an overview and critical analysis of the current application and implementation of 3D data to CH objects of any kind, independent of purpose or approach.

Collection of 3D data can be done by a variety of methods using a variety of tools, and has been extensively explored and described in prior reviews [3, 4]. Although these methods follow many of the same principles, revolving around an imaging system and the post-processing of its data, some differences in their specifications and functionality causes some to be better suited than others depending on the characteristics of the object or demands of the project [5]. Additionally, the long post-processing stage necessary in any 3D workflow consists of many steps, each of which use tools that might introduce alterations to the data to serve a specific purpose. The final results of a 3D documentation process are therefore equally dependent on the post-processing and

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application, as well as acquisition. Resulting data can vary from point clouds, to triangulated meshes, to fully textured and optimized 3D models depending on which step the producer regards as final.

Development of easy-to-use 3D data acquisition tools has led to the (CH) field adopting these methods more readily. A prime example is the subsequent increase in virtual museums in the CH field [6], which are collections of 2D and 3D objects of various interests that can be accessed through electronic media [7]. As an application, visualization in such a way is perhaps the most obvious result of 3D data, and fulfils the objective of making the objects accessible to an online audience. The traditional museum approach is also familiar to audiences, and follows the ’see but don’t touch’ rule-set. Utilizing this approach brings the objects to the digital space, but makes limited use of the other opportunities provided by 3D models. For example having the possibility to look at cross-sections of the objects, or inspecting the object under different lighting conditions.

While the concept of virtual museums have been around for a long time, extensive work is still being done by the likes of the Virtual Multimodal Museum (VIMM)[1] and The European Museum Academy[2] to aid in decision-making, development, and standardization of virtual museums in the GLAM-sector (Galleries, libraries, archives, museums) across the digital space. This is to attempt to follow this rapid development of 3D acquisition and visualization techniques, as well as the subsequent flood of data. Some prominent virtual museums are Virtual Museums of Małopolska,[3] and Digitalt Museum.[4] Additionally, a few museums has taken the step towards providing digital viewing of their objects without developing a whole virtual museum platform: National Museums Scotland,[5] The Louvre Museum,[6] and The British Museum[7]are some examples.

The virtual museum is perhaps the application which represents the elements from the traditional heritage conservation perspective and computer science perspective most equally, and museum researcher Suzanne Keene captures an important aspect of moving towards CH in the digital space with the quote: “*We used to build collections of objects. Now we can make collections of information, too*” [8]. While her comment regards several things, including metadata and semantics, 3D objects might be appended with additional information as well. Cross sections from x-ray data, annotations, and different textures are a few. But, it is important to remember that 3D objects are not tangible objects in themselves, rather visualization of information about tangible objects. The visualizations of CH in virtual museums are only based on the information we are able to acquire in an acquisition process. Careful ethical considerations must then be made on how to visualize and communicate this to an audience, without introducing conjecture or misinterpretation in the presentation. This is perhaps especially true in the museum setting, but has equal relevance for any application of reality-based 3D methods. Heritage objects curated by museum organizations follows standardization guidelines provided by organizations like ICOM [9] and ICOMOS [10], and while work is being done on implementing 3D in virtual museums in a standardized way [11–13], there is still a lot of gaps in knowledge and ethically justifiable workflows. As such, the virtual museum is an example of the general digitization process of the CH field, but the contemporary and state-of-the-art projects and implementations reviewed here often take several steps away from the traditional museum setting.

Application of 3D data of CH objects is only partially covered by museums, either physical or virtual. Standalone projects, non-profit organizations, research institutions, production companies, and private persons contribute a significant portion of the 3D data that is available online. Furthermore, the data of this varied field is being used for many other applications than just digital viewing of the object, even though this is an obvious, popular, and easily implemented utilization. As this varied ensemble might not be bound to some institution or larger organization, they might not adhere to any sort of museum or heritage standards or regulations in the case of digitizing CH, and are therefore free to do “what they want” in order to get the best results. What can be classified as the “best result” again depends on the application, and literature and projects often lists the many platforms 3D data can be applied to.

Some recurring proposed and tested applications for 3D models of CH objects are: visualization and dissemination [14–16], simulation [17, 18] education and training [19–21], and research [22–24]. Additionally, audience interaction is a factor explored in implementations that feature gamification principles. At a glance, these are very broad suggestive implementations that are very different in their context and content. Papers and projects that utilize 3D for CH often phrases that it *might* lead to new knowledge and insights [16], but this application is in most cases still in a very early phase. New developments for utilization of 3D also gives virtual reality (VR), augmented reality (AR), and mixed reality (MR) increased

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[1] https://www.vi-mm.eu/

[2] https://europeanmuseumacademy.eu/

[3] https://muzea.malopolska.pl/

[4] https://digitaltmuseum.no/

[5] https://www.nms.ac.uk/

[6] https://www.louvre.fr/en/online-tours

[7] https://www.britishmuseum.org/collection

uses and applications in many fields, but similarly lacks designated guidelines for ethical implementations and requirements in terms of quality and semantics. Especially with CH objects that are sensitive to conjecture.

Currently there is a lot of work focused on making the application of 3D data for CH more concrete; researching and developing both standards and workflows that should help institutions apply 3D to their own collection in a more uniform way. The prior mentioned reports and research papers agree that there is still a lack of knowledge for CH institutions regarding 3D implementation and processing, and that this is required to make the full utilization of 3D for CH a reality.

There is on the other hand no shortage of research conducted on the use of 3D in the CH sector. New applications that are being investigated includes conservation [25], change monitoring [26, 27], visualization [28], additive manufacturing [29, 30], BIM (Building Information Modeling), also known as HBIM (Heritage Building Information Modeling) [31, 32], and dissemination methods [33] just to mention a few. Recent investments and grants like CHANGE,[8] the n-Dame Heritage ERC project,[9] Data Service for Complex 3D Data in the Arts and Humanities,[10] JPI CH,[11] and Perceive[12] also signifies that this field will continue to grow in the future.

This paper reviews results from contemporary and state-of-the-art projects, and how they make use of 3D for CH purposes to see if the initial imagined potential and value of 3D digitization has been met, surpassed, or limited. Additionally, we take a close look on the various frameworks in which 3D data is presented, and if interoperability might be a concern between projects. Longevity and use of the end results is also something that is scrutinized, in an attempt to evaluate the impact that these projects might have had based on the results they present. The reviewed projects, institutions, guidelines, and tools have been selected based on their recurring appearance in academic papers as well as their visibility when browsing for the subject online. We deem that since these projects are the most visible, they might also be the most influential for new projects in the future.

Section "Prior reviews and existing projects" presents various prior reviews on 3D CH data, and takes a close look at some of the most relevant selected projects. Workflow proposals for data acquisition and processing is presented and scrutinized in Sect. "Workflows for acquisition and processing of 3D data", and Sect. "Heterogeneous data and interoperability issues" presents some apparent issues with utilizing 3D CH data. In this section we also highlight a few options for solutions that are not as visible as the reviewed projects. A discussion on the presented data is done in Sect. "Discussion", before summarizing and providing conclusions in Sect. "Conclusion".

Prior reviews and existing projects

Previous reviews of applications of 3D data in the CH sector has mostly been from specific approaches, for example acquisition methods [3, 34–36], data fusion [37, 38], and documentation approaches [39–41]. Most of the papers in these reviews are very technology-oriented, and are most often concerned with the acquisition technology or post-processing of the data. As such, they primarily lean towards the discipline of computer science and the development of technology and theories to produce 3D data. This leaves an emptier space for the application of the end results, as the theorized utilization is not often described after acquisition is completed. This is trend is also found in many guidelines and proposed workflows for 3D and CH, which also mostly regard the acquisition of data.

One of the latest addition to these reviews is the final study report from the EU Horizon 2020 funded VIGIE 2020/654,[13] led by Cyprus University of Technology. This study has sought to map current formats and standards used for measuring the quality of current 3D digitisation, and propose different measures that should be implemented to ensure high quality of the resulting data. Summarized, they again found that there is a great variety in approaches, tools, formats, and knowledge-bases, highlighting the urgent need for standardization of workflows to increase interoperability of 3D data in the CH sector. This is similar to the conclusion of prior studies. Furthermore, they increasingly emphasized the evaluation of quality of the 3D object, and how it relates to the complexity of the tangible object. Both 'quality' and 'complexity' is hard to define, but they interpret them as a measure of 15 different parameters. *Quality* is evaluated by: the materials of the object, structural health monitoring, 2D image data, 3D geometric data, texture, scale, and spectral characteristics. *Complexity* is evaluated by: Team, Environment, Software, Hardware, Preprocessing, Stakeholder's requirements, Object, and Project. Note that each of these parameters has several sub-parameters.

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[8] https://change-itn.eu/

[9] http://www.ndameheritage.map.cnrs.fr/

[10] https://blogs.brighton.ac.uk/3ddataservice/

[11] https://www.heritageresearch-hub.eu/

[12] http://perceive-horizon.eu/

[13] https://digital-strategy.ec.europa.eu/en/library/study-quality-3d-digitisation-tangible-cultural-heritage

As their selected parameters are not all numerically quantifiable, the final quality metric relies on a subjective evaluation. This would require expertise of both the tangible object and the 3D process to land on a good holistic evaluation, where interdisciplinary discussions would be essential. Variations in knowledge is a fundamental problem faced in this standardization process, as it is little common ground to originate from between CH and computer science. This is an observation also made in other investigations[42] and fields [35], which emphasizes the same problem. A proposed app called DAPMS (Data Acquisition Process Management System) is under development as a result of the study, which could make it easier for other institutions to provide evaluations of the proposed parameters of the acquisition and processing of their 3D data.

Several prior studies have also used this approach: At the University of Novi Sad, Serbia, they sought to develop a system which assists in the selection of a 3D digitization method based on the object characteristics [43]. While their approach of describing the object and desired data does not fall under the same ’quality’ and ’complexity’ umbrella terms, the selected parameters are very alike. Similar parameters for method selection is also listed by Pavlidis et al. [40] in their “9-Critera Table”, and Guillaume and Schenkels “Best Practice Checklists for 3D Museum Model Publication” [44] also emphasizes the complexity that these parameters introduce.

But while all these papers highlight aspects which would affect the quality of a 3D data acquisition process for CH, they provide little in terms of standards or quality evaluation tools for each of them. As prior mentioned, many of the parameters entirely depends on subjective evaluation or project objectives. Suggested tools therefore does not necessarily help the team collecting the data make objective decisions about the parameters, but rather list the parameters they would have to make subjective decisions about. And, as the nature of 3D data is alterable, the end result of any 3D project could have great variation, even when utilizing similar methods. It is again also clear that most of the research regard the acquisition of 3D data, while the application of said data gets much less attention from a research perspective. Data is collected, the models are produced, and they are visualized using one of the many 3D viewers available. Rarely do papers tackle the issue of ’what happens next?’, leaving the application and storage of the data, which might be a cause for the interoperability issues in the first place, to individual institutions[45].

A better source for reviewing this issue is the many current 3D digitization projects for CH. These may or may not have connections to research, but are nonetheless cited as results of research methods. As with papers, their purpose and objective varies, resulting in great variation in what data is available. In an attempt to categorize some of the projects, we have made a distinction in this paper between what we regard as data collectors and data repositories out in the field.

Data collectors

Classified as data collectors are the projects which in addition to visualizing CH data in 3D, also stand for their own data acquisition. Prominent, non-profit, data collectors are CyArk,[14] ZamaniProject,[15] ScanTheWorld,[16] GlobalDigitalHeritage,[17] and Arc/K.[18] Some of these projects also develop applications for viewing the 3D data on their website, like CyArk’s narrated virtual tours and Zamani Projects plans and sections viewer. Note that these projects are primarily designed for audience viewing of the data, and does not necessarily contribute quantifiably relevant research data.

The Zamani Project is one of the longest running CH digitization projects. It was founded in 2001, and posted its latest fieldwork in November 2021. Consisting of researchers from the University of Cape Town, their fundamental objective is the documentation of heritage sites, and the analysis, communication, and training that can be derived from this. At the time of writing, they have documented over 250 structures and sites across Africa and South-east Asia, and provide media ranging from 3D models, cross sections, point clouds, and GIS, available from UCT’s repository.[19] CyArk is another of the longer running 3D projects for CH, being founded in 2003 and worked at over 200 sites in over 40 countries. Their objective is similar to that of the Zamani Project, and provides open access to all of their 3D data through Open Heritage 3D.[20] Both of these projects make use of well known tools and methods to acquire their 3D data, with semi-transparency regarding tool specifications and post-processing stages. Regardless of object quality, the phenomenon of varying geometric resolution in their 3D data is clearly apparent when looking through their collections. Not to mention the technological developments that have been made in the last 20 years, which renders some of their data clearly aged. Heritage objects belonging to the same heritage site is digitized differently by the two projects, apparent in 3D models of temples from the

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[14] https://cyark.org/

[15] https://zamaniproject.org/

[16] https://www.myminifactory.com/scantheworld/

[17] https://globaldigitalheritage.org/

[18] https://arck-project.org/

[19] https://zivahub.uct.ac.za/zamani_project

[20] https://openheritage3d.org/

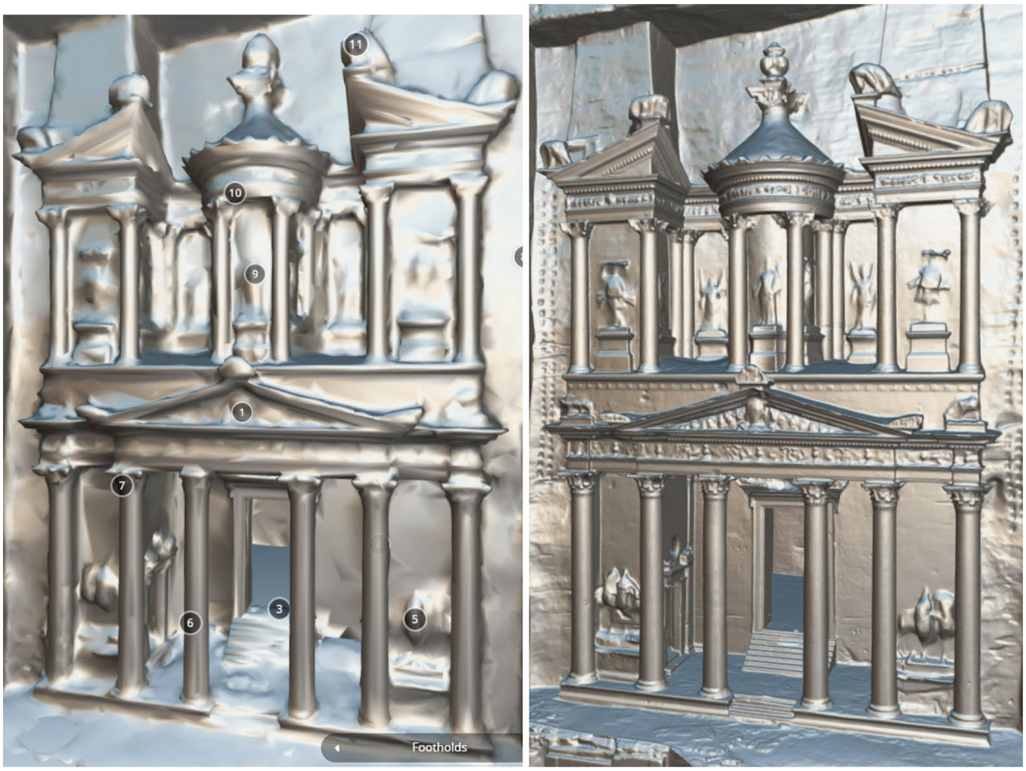

Fig. 1 Left: *'Petra' Model by RaizeNewMedia.* Right: *'Petra' Model by Zamani Project*

Bagan city, Myanmar. “Eim Ya Kyaung” was modeled by CyArk[21] and “Temple 1085” by Zamani Project.[22] Under inspection, both geometry and texture resolution is noticeably different between the objects. So while their objectives and acquisition tools are very similar, their end results and applications would be evaluated differently by an objective metric like that proposed by VIGIE2020/654 and the University of Novi Sad [43].

In addition to non-profit organizations there are also several production companies that makes a business model of generating 3D data, with a specialization in CH. Production companies that non-exclusively work with CH like Rigsters,[23] RaizeNewMedia,[24] Calidos,[25] Quixel,[26] 7Reasons,[27] and Overhead4D[28] are prominent in their contribution of the 3D CH data that os available on the web. Private companies are traditionally more secretive with their acquisition tools and methods, which in many cases are also custom and proprietary. This might also cause issues in quality evaluation by other institutions if insufficient metadata and paradata is collected.

As another example of how 3D acquisition can be very different even when done by professionals, we will visually compare two models of the same object done by another two producers. The Al-Khazneh temple in Petra, Jordan has been modeled by both the company RaizeNewMedia[29] and by the Zamani Project.[30] They have both posted the models on Sketchfab, which is a 3D viewer that allows for inspection of the models geometry, textures, and UV projections. A comparison on geometry can be seen in Fig. 1, and with color textures in Fig. 2.

A visual inspection of this example makes it is hard to evaluate which model is of higher quality, as one seemingly features better geometry while the other features better colors. The Zamani Project utilized a laser scanner for their acquisition, while RaizeNewMedia does not mention what tools they use. The Zamani Project laser

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[21] https://skfb.ly/6RO7U

[22] https://skfb.ly/o6OnY

[23] https://rigsters.com/

[24] http://www.raiznewmedia.com/

[25] https://www.calidos.cat/

[26] https://quixel.com/

[27] https://www.7reasons.net/?lang=en

[28] https://overhead4d.com/

[29] https://skfb.ly/6xBIP

[30] https://skfb.ly/ISnJ

Fig. 2 Left: *'Petra' Model by RaizeNewMedia*. Right: *'Petra' Model by Zamani Project*

scan was a part of the Siq Stability Project[31]’ by the Italian Ministry of Foreign Affairs, used to monitor slope instability in the sandstone cliffs around the heritage site. The visualization we see is just a simplification of the raw data used for the monitoring, where color is an non-contributing factor to the project objectives. For this purpose, the 3D model is of high enough quality for its designated application. While RaizeNewMedia’s model does not mention its modeling objective, it might have been for a more general application. It might therefore be more flexible in its uses, but with less conservation or research merit. As such, we cannot evaluate the quality of 3D models for CH from a single metric, as the creation purpose would channel the raw data into a specific form and produce different end results. Forms and resolution of data directly correlates with its data size and format, which again would decide how inter-operable it would be. 3D data repositories and 3D viewers have different support in what scales and formats of data they are able to process, and users must therefore make specific choices about limiting what data they are able to include.

Data repositories

Different from the data collectors, we have the data repositories. Data repositories are applications, websites, databases, or institutions whose purpose is to store 3D data of CH objects collected by a variety of users. While some also produce data themselves, it is not their primary objective. Some of these repositories could in many ways be compared to virtual museums, where users can freely browse and inspect 3D models without downloading them localy, but without the designated museum approach. Others are purely databases for management and long-term data storage, and offer no online visualization whatsoever. Some examples of current data repositories are Google Arts and Culture[32], Europeana[33], Golden Agents[34], TARA[35], Open Archives[36], Open Heritage 3D[37],

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[31] https://amman.aics.gov.it/wp-content/uploads/2020/01/AICSfactsheet-petraSiq.pdf

[32] https://artsandculture.google.com/

[33] https://www.europeana.eu/en

[34] https://www.goldenagents.org/

[35] http://www.tara.tcd.ie/

[36] https://www.openarchives.org/

[37] https://openheritage3d.org/

Aioli[38], Nextcloud[39], Texas Data Repository[40], Smithsonian 3D[41], MorphoSource[42], Historic Environment Scotland[43], LOCKSS[44], REKREI[45] (Formally known as Project Mosul), and Morbase[46].

Common among all of these is that they open for users from varied institutions to upload data to their platform. They are not necessarily aligned to a specific project, but some are limited to certain types of CH objects. MorphoSource primarily focuses on biological skeletal material, and Golden Agents focuses on items from the Dutch Golden Age. Few, if any, seem to feature any sort of quality control or accuracy requirement for uploading 3D CH data, perhaps due to the lack of universal agreed-upon quality standards for different sized objects. Resolution of the objects then depends on the data acquisition and processing of each individual object. But, they do feature requirements for metadata, providing some parameters for evaluation for users who want to download or utilize the data for different purposes. Out of the reviewed repositories, Europeana seems to be the most developed in terms of having requirements for making collection data available through their network. They have strict requirements for metadata formats and licensing status, but leave the quality assessment of the published data up to each institution. Common metadata standards are CARARE,[47] LIDO,[48] METS,[49] and EDM,[50] where EDM is specifically developed for uploading CH data, including 3D, to the Europeana platform. In terms of licensing of the data and availability for the audience, a review by McCarthy and Wallace[46] summarizes how a lot of CH institutions implements the GLAM open access policies. Apart from metadata schemas and licensing, the infrastructures of the repositories are all very different.

In a survey done by the team at PURE3D in 2021 to understand requirements for 3D web infrastructures by 3D CH data collectors, few respondents answered that they had a plan for preserving their data in the future other than uploading to one of these repositories[47]. Following the assumption that the application of acquired 3D data has not yet been properly developed in the field, this short-term view on the acquired data might further suggest at this limited utilization. Their survey summarizes with a priority list for new and current data repositories and 3D viewers specifically designed for CH data, based on the responses in their survey. A great amount of desired features are familiar to any academic environment, such as ID generation for projects and objects, citation styles for 3D objects, and peer-reviews for model uploads or the ability to filter by this. Implementation of such features would make it easier to distinguish between research data and commercial/creative data, and allow for a scientifically grounded approach to 3D CH on the web. Other desired research functions include measurement tools in the 3D viewers, multi-object viewing, and scripting implementation. This could permit for a more objective evaluation of a repository's content, and review the quality of different 3D models compared to each other.

In Table 1 we have provided an overview of the selected projects and institutions in this review, which specifies their features and category as well as listing the objective of the project as listed on their website.

A prior review of workflows and documentation approaches proposes that one of the reasons for the current 'disorganization' of 3D CH data is that the research method of 3D data collection for CH has not been recognized as academic in nature [48], but is rather leaning towards being a more creative and artistic appliance to the CH academic field. While *computer graphics* is a recognized and well-established discipline, the prior mentioned challenges of ethics, conjecture, and quality control apparent in CH digitization has yet to receive the same treatment. This might be due to the lack of specialized educational or research programs for the discipline, and its close relation to creative computer graphics by using the same software and workflows. Approachable software and audience interest also generate a lot of publicly-created data which blends together with the data originating from research, making distinctions hard without quantifiable methods and standardized parameters. While specialized 3D data from research projects mentioned in Sect. Introduction and "Prior reviews and existing projects " are obviously scientific in nature, it might be hard for an uneducated eye to distinguish them without any evaluation tools. As such there is significant overlap between the two fields, but less specialized approaches to tackle the specific issues within this overlap. There are currently several institutions that exclusively produce 3D CH data from a research perspective;

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[38] http://www.aioli.cloud/

[39] https://nextcloud.com/about/

[40] https://dataverse.tdl.org/

[41] https://3d.si.edu/

[42] https://www.morphosource.org/

[43] https://www.historicenvironment.scot/archives-and-research/

[44] https://www.lockss.org/

[45] https://rekrei.org/

[46] https://montemorbase.com/

[47] https://pro.carare.eu/en/introduction-carare-aggregation-services/carare-metadata-schema/

[48] https://cidoc.mini.icom.museum/working-groups/lido/lido-overview/lido-schema/

[49] https://www.loc.gov/standards/mets/

[50] https://pro.europeana.eu/page/edm-documentation

Table 1 Overview of reviewed Organizations and Projects

Nr.	Name	Data Acquisition	Data Storage	Objective	Open Access	Category
1	3DOM	✓	✓	Measurement Research	✓	Research Group
2	7Reasons	✓	x	Audiovisual Production	x	Production Company
3	Aïoli	✓	✓	Object Annotation	✓	Collaboration Platform
4	Arc/K	✓	x	Digitization	✓	Non-Profit
5	Calidos	✓	x	Audiovisual Production	x	Production Company
6	CARARE	x	x	Network	x	Non-Profit
7	CHANGE	✓	x	Research	✓	EU Marie Curie
8	CIPA	✓	x	Heritage Documentation	x	Network
9	Cultlab 3D	✓	x	Research and Development	x	Research Group
10	Cyark	✓	x	Digitization	x	Non-Profit
11	Darklab	✓	✓	Research	✓	Research Group
12	DARIAH	x	✓	Data Management	✓	Network
13	Digital Heritage Lab	✓	x	Research	✓	Research Group
14	E-RHIS	x	✓	Infrastructure	✓	EU Project
15	Europa Nostra	x	x	Heritage Network	x	Network
16	Europeana	x	✓	Infrastructure	✓	EU
17	Global Digital Heritage	✓	✓	Digitization	✓	Non-Profit
18	Golden Agents	x	✓	Digitization	x	Research Group
19	Google Arts and Culture	x	✓	Infrastructure	x	Collaboration Platform
20	HERALD (Oasis)	x	✓	Data Management	x	Collaboration Platform
21	Historic Environment Scotland	✓	✓	Research and Digitization	✓	Public Body
22	Historic VR	✓	x	Digitization	x	Production Company
23	LOCKSS	x	✓	Data Management	x	Data Repository
24	Morbase	x	✓	Research and Digitization	x	Production Body
25	Morphosource	x	✓	Data Management	✓	Non-Profit
26	NEMECH	x	x	Network	✓	Network
27	NextCloud	x	✓	Open Source Collaboration	✓	Collaboration Platform
28	Open Heritage 3D	x	✓	Data Management	✓	Non-Profit Data Repository
29	Overhead4D	✓	x	Audiovisual Production	x	Production Company
30	PRESIOUS	✓	✓	Research	✓	EU Project
31	Quixel	✓	x	Asset Prodution	x	Production Company
32	RaizNewMedia	✓	x	Audiovisual Production	x	Production Company
33	REKREI	✓	✓	Digital Restoration	✓	Non-Profit
34	Rigsters	✓	x	Audiovisual Production	x	Production Company
35	ScantheWorld	✓	✓	3D-Printing	✓	Non-Profit
36	SEADDA	x	x	Research	✓	EU Project
37	Smithsonian 3D	✓	✓	Research and Development	✓	Research Group
38	Stanford Scanning Repository	x	✓	Research	✓	Data Repository
39	STARC Repo	x	✓	Data Management	✓	Research Group
40	TARA	x	✓	Data Management	✓	Data Repository
41	tDAR	x	✓	Data Management	✓	Data Repository
42	Texas Data Repository	x	✓	Data Management	x	Data Repository
43	Vasabas	✓	✓	Digitization	x	Museum
44	Visual Computing Lab	✓	x	Research	✓	Research Group
45	Zamani Project	✓	x	Digitization	✓	Non-Profit

Table 2 Overview of reviewed guidelines and their content

Organization	Arc/K	CIPA	Europeana	Federal Agencies Guidelines Initiative	IIIF	Riksantikvar-ämbatet	The European Commission	The London Charter	Cultural Heritage Imaging
Acquisition	✓	✓	x	✓	✓	✓	✓	x	✓
Metadata	x	✓	✓	✓	✓	✓	✓	✓	✓
Paradata	x	x	x	x	x	x	✓	x	✓
Post-Processing	x	x	x	x	x	x	✓	x	✓
Storage	x	✓	✓	✓	✓	x	✓	✓	✓
Quality Evaluation	x	x	✓	✓	x	x	x	x	x
Viewing	x	x	x	x	✓	✓	x	x	x
Licensing	x	x	x	x	✓	✓	✓	✓	✓
Digitization Purpose	x	x	x	x	x	✓	✓	✓	x
Hardware Listing	✓	x	x	x	x	✓	✓	✓	✓
Software Listing	x	x	x	x	x	x	✓	✓	✓

Visual Computing Lab,[51] 3DOM,[52] Darklab,[53] Digital Heritage Lab,[54] and Cultlab 3D[55] are a few. While general and specialized research is important, these institutions could also increasingly move towards utilizing educated workflows that does not narrow their data to a specific research question, but rather apply their research to more universal data which is similar to what is being developed by other CH institutions to be fairly scrutinized. Only when the data have some universal similarities can they be evaluated for quality by some standardized metric, but we immediately recognize the limitations this would put on the research that could be conducted.

There are a myriad of guides and workflows for processing 3D data the 'optimal way', both in relation to CH, research, entertainment, and in general. In the next section, we take a look at how different institutions propose to make a 3D object of high quality, and how they evaluate this.

Workflows for acquisition and processing of 3D data

Similar to the wide application purposes of 3D data, existing workflows for 3D data acquisition encompass a great amount of uses. While some acquisition workflows are designed with CH in mind, they might not differ too much from creative purpose workflows. As such, most proposed workflows for CH orient around data management, good practices, and general purpose solutions. Examples of institutions that contribute guidelines to 3D workflows are The European Commission,[56] Riksantikvarieämbetet,[57] Federal Agencies Guidelines Initiative,[58] Europeana,[59] The London Charter,[60] Cultural Heritage Imaging,[61] and the International Image Interoperability Framework (IIIF) Consortium.[62] In Table 2 we have provided a table that covers what features each proposal provides suggestions to. This includes features like suggested tools for different objects, acquisition and management processes, documentation practices, quality evaluation, and final data implementation.

As an example of acquisition guidelines, we will take a closer look at the method of photogrammetry. Photogrammetry is one of the most utilized methods for 3D model creation, and is approachable to novices as it does not require expensive hardware or software. Arc/K is a non-profit CH digitization organization that has produced a guide on how they do photogrammetry for CH,[63] and lists some requirements and suggestions for technical specifications and imaging practices. But as is the pattern with the reviewed projects, they do not mention post-processing or quality evaluation of the final model. Similarly, CIPA, the International Organization

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[51] http://vcg.isti.cnr.it/

[52] https://3dom.fbk.eu/

[53] https://www.darklab.lu.se/projects/

[54] https://digitalheritagelab.eu/

[55] https://www.igd.fraunhofer.de/en/industries/cultural-and-creative-economy/3d-scanning.html

[56] https://digital-strategy.ec.europa.eu/en/library/basic-principles-and-tips-3d-digitisation-cultural-heritage

[57] https://www.raa.se/in-english/outreach-and-exhibitions/guide-for-publishing-3d-models/

[58] https://www.digitizationguidelines.gov/guidelines/digitize-technical.html

[59] https://pro.europeana.eu/project/3d-content-in-europeana

[60] https://www.londoncharter.org/index.html

[61] https://culturalheritageimaging.org/

[62] https://iiif.io/news/2022/01/11/new-3d-tsg/

[63] https://arck-project.org/photogrammetry-learn-how-to-shoot/

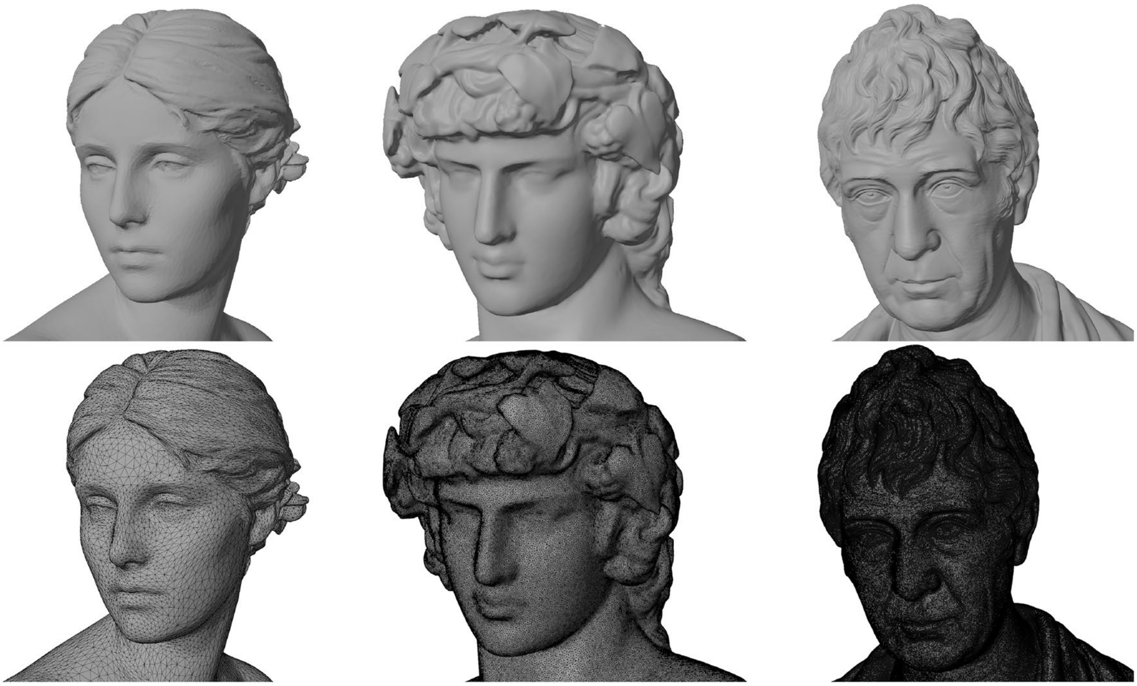

Fig. 3 Tessellation resolution difference for 3D objects of similar size

for Heritage Documentation, summarizes their photogrammetry guidelines in single document called The 3x3 Rules.[64]

Another guide to photogrammetry is done by the developers of the Unity game engine, who provides a more in-depth workflow from acquisition to implementation of the finalized 3D object.[65] Note that they specify that their guide is aimed at game development and the creation of a 3D asset meant to be visualized in real-time in a virtual environment. As such, it has limitations in its possible resolution in both geometry and texture. Such a distinction aids the ones responsible for the data acquisition to make decisions about their finalized object, as the application has certain restrictions. Arc/K provides no such distinctions, even within the field of CH. These are just two of the many tutorials, guidelines, and workflows suggested by the projects and institutions referenced in this review. This open-ended approach could be both a blessing and a curse, as the unrestricted acquisition *might* yield high quality results, but also opens for erroneous and disorganized realization. Recognizing that different applications of 3D data have different limitations could help guide standardization practices for different platforms, and distinguish between good and bad quality models in different categories. CH objects have great and varied challenges where no approach could be deemed superior, so a mixture of the mentioned restriction and freedom might be the best solution.

For CH objects with these varied complexities and characteristics it is normal to implement several 3D data acquisition methods to overcome the different challenges they propose[49]. Often different segments of the object have different resolution requirements to be rendered accurately [50], or segmented surface characteristics which requires a specialized approach [51]. A single workflow might then not encompass all the solutions to these different challenges. Additionally, small changes in a workflow might result in drastically different results. For example, selecting a high enough resolution during acquisition directly relates to how much post processing you have to do later. If the captured data has a really high resolution you would have to do more post-processing to end up with a usable 3D object, but capturing the object in lower resolution might yield inaccurate results with less opportunities for utilization. This resolution problem is intrinsic to the desired quality evaluation of 3D objects, but must also be weighted against factors like object size, surface characteristics, and data size. Psychovisual evaluation and image quality metrics have been tested to see if they can be used for 3D model evaluation in different digital spaces, and what factors renders a 3D object

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[64] https://www.cipaheritagedocumentation.org/wp-content/uploads/2017/02/CIPA__3x3_rules__20131018.pdf

[65] https://unity3d.com/files/solutions/photogrammetry/Unity-Photogrammetry-Workflow_2017-07_v2.pdf

Fig. 4 Left: No visible UV seams or pixelization. Middle: *Visible UV seams and pixelization when zooming.* Right: *UV segmentation.* Model: "Nile" (https://skfb.ly/6TDJI) by Rigsters

visually realistic [52–55]. These experiments have yielded limited results, and would only contribute to subjective evaluation. Issues with some of these experiments might be the viewing conditions, as well as the lack of specified purpose for the 3D objects. 3D objects might be evaluated of different quality from different viewing distances, and objects of less complexity might also be easier to visualize accurately with less geometry. Several automatic metrics also exist, but are targeted at visual quality saliency [56–62]. As such, the simple increase in 3D resolution does not necessarily increase the quality of the 3D object, and might have little to no effect on both subjective or objective evaluations. Differences between subjective and objective evaluation of 3D objects is something that should be explored further.

The Virtual Museums of Małopolska, the British Museum, and National Museums Scotland have all published 3D objects of similar size from their collection on Sketchfab, but with significant differences in end-result-visualization. Figure 3 is a wireframe render of busts taken from each collection which have approximately the same real-life size, but where the 3D resolution is quite different. "*The Bust of Róża Loewenfeld*"[66] from the Virtual Museums of Małopolska feature 60.000 triangles, "*Antinous*"[67] from the British Museum has 1.1 million, and the "*Joseph Hume Marble Bust*"[68] from National Museums Scotland has 3.8 million. Nonetheless they are all 3D objects of seemingly good visual quality when inspected on the 3D platform.

This perceptual variation in resolution highlights the significance of the application of the 3D model, as different uses might have drastically different demands for data. All of these busts might be suitable for the online viewing exemplified here, but feature different suitability for research on the objects' surface. In theory one could say *the higher resolution the better*, but the practical reality is that 3D objects of high resolution is incredibly computationally heavy. Large quantities of data is challenging to both visualize and preserve, especially for institutions who are not based in research or development, requiring tremendous hardware infrastructure. A new project called EUreka3D[69] seeks to alleviate this issue for smaller heritage institutions. There also exists some methodological solutions for multi-resolution encoding [63] and progressive transmission of data [64], allowing users to view individual, segmented parts of the data at a time. Regardless, it is most often necessary to apply post-processing on the data, to simplify and tailor it for a specific use. As such, the CH projects reviewed here rarely works with the raw data captured by a 3D acquisition process for long, and apply the prior mentioned alterations to create a more suitable result. They generally want to avoid cases where the necessary post-processing jeopardizes the high-accuracy data which was collected, to not render the high acquisition demands obsolete. This issue can be tackled in a few different ways, and some proposed workflows recommend different approaches for retopology.

Retopolgy encompasses changing the 3D objects polygonal structure to either be more suitable for a specific 3D environment or to reduce the amount of polygons

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[66] https://skfb.ly/ZMvC

[67] https://skfb.ly/6nDV9

[68] https://skfb.ly/6TBDr

[69] https://pro.europeana.eu/project/eureka3d-european-union-s-reconstructed-content-in-3d

Fig. 5 Left: *Image of Lamassu from the British Museum* Right: *Model of the same Lamassu by CyArk*

without removing too much of the objects captured shape. This is most commonly proposed to be done automatically by a mesh simplification algorithm as it is fast and efficient. But manual retopology is also often mentioned as an approach [44, 65]. A review of mesh simplification algorithms is done by Cignoni, P., Montani, C., and Scopigno, R. [66], and highlights that different segments of 3D objects behave differently when simplified by different simplification algorithms. Some approaches are better for rough surfaces, while other are better for hard angles. While both algorithmic simplification and manual retopology steps away from the high resolution data collected during the acquisition, and as a result steps further away from the ground truth, they have different benefits based on the subsequent application of the 3D model. Mesh simplification simply decimates the object to be more easily rendered in 3D viewers, while manual retopology is a more time-consuming process which restructures the object in a specific way.

Additionally, texture acquisition and UV projection are issues which will greatly affect a 3D models perceived quality. If one is to look at 3D objects from a distance, one could get away with lower resolution in the geometry, texture, and the UV projection. But this is rarely the case, as one of the advertised benefits of digitizing tangible objects is the possibility to look closely at the object surface. UV seams and low texture resolutions become visible when you zoom in, which would detriment the benefits gained by zooming. The color and surface representation of 3D objects are both large fields of research, urge the reader to explore other reviews about color [67, 68], reflection models and BRDFs (Bidirectional Reflection Distribution Functions) [69, 70], and UV projection [71, 72] in relation to the 3D topic covered here. An example of effects from these factors can be seen in Fig. 4.

These are just a few of the issues which projects utilizing 3D would have to make decisions about, and documentation of their selected approach and workflow is essential for an evaluation of the end result. But while the documentation of these technical specifications and approaches are integral to a 3D project, in many cases they also drown out the question of why the digitization was conducted in the first place. This observation was first reported by Pfarr-Harfst in 2016[48], and while there have been improvements to contextualizing the data in contemporary research, many projects still suffers from the same issue.

In many projects the objective is summarized as the paraphrase: "*the 3D documentation of CH to provide open access for education, research, and audiences*". While noble, this is very open ended and could potentially have limited use if the aspects of the data is not of a high enough quality for a certain application. The projects and workflows reviewed here may in some cases produce the data, but not the tools or platform for which they created them. Figure 5 highlights the importance of quality control for the 3D models of CH, as some published data has many apparent faults in their accuracy.

In her review, Pfarr-Harfst proposed a documentation practice that highlights the 'prior', the 'during', and 'subsequent' situation of both the heritage object and the project data[48]. This might be an important step the field should take to be more academically recognized, as we would be able to more clearly move away from using CH as an object for computer graphics visualization and towards using computer science as a tool for CH preservation.

Current reviews for 3D implementation in CH highlight the necessity to quantify the accuracy of the 3D data in an objective, homogeneous, and semantic way, while suggested workflows provide subjective and indeterminate tools to do so. This divide is a cause for concern for the merit of 3D CH data, and future research should exert itself to contribute to this gap in information. But the apparent and necessary variation in approaches, along with the great variation of the objects themselves, signifies that a single, standardized workflow for 3D in CH might be an impractical approach.

Heterogeneous data and interoperability issues

Another possible reason for the data clutter in the 3D CH field is precisely this variation of objectives with limited specifying documentation. This ties back to the lack of long-term support and application of the collected data, and overemphasis on acquisition methods relative to research questions. What we have ended up with is heterogeneous data that might have limited interoperability and little contribution to other areas than computer graphics visualization, which is not unique to the CH field. There is a significant semantic difference between using 3D for visualization and for the research of the tangible objects, as one emphasizes observer perception and the other measures quantitative parameters. Various approaches will also weigh different parameters of an acquisition process in a unique way, perhaps leading to specialized data that is not easily used for other applications. While it may not be an objective for some research approaches to make their data universally applicable, extensive restrictions on the workflow and post-processing might render the data or research results to not be reproducible in other environments. If this ends up being the case, the legitimacy of the methodology might be jeopardized, as it might only be valid under very specific conditions.

Digital projects for CH that utilize 3D data will always be multimodal, and weighs different data types based on the project objective. It is an intrinsic part of any 3D workflow that the data undergoes a lot of change and travel through different software. Even projects that exclusively want to capture the geometry of objects, disregarding color and texture, are still dependent on temporary data like 2D images or point clouds, meaning that there is no clear divide between 2D and 3D workflows. Maintaining the different modalities, even if it might have no practical use to the current project might lessen this heterogeneity issue. This ties back to Pfarr-Harfst's notion of documenting the prior, the current, and the subsequent in 3D digitization processes, and different data formats validating this could provide sufficient academic evidence of the results of a 3D processing stage for CH.

For example, while research have been conducted on reconstructing the missing shape of CH objects using Poisson reconstruction [28] and shape recognition[73], there is no way of validating how accurate this is in reality. And while this is the case, there might be little difference between using this method and modeling by hand, apart from ethical or subjective considerations. A model that has been processed in such a way would also be unsuitable for suggested applications like change monitoring, where the introduced conjecture already renders the 3D object ethically improper for ground truth comparisons. Other application workflows, like 3D printing, uses a file format which reads the data in way where a watertight 3D model is essential. In which case a hole-filling process is inevitable. ScanTheWorld[70] is a repository designed for sharing 3D data of cultural artifacts for the purpose of 3D printing, and therefore does not support objects or formats which are unsuitable for this task. Other applications might not have this demand, and while a 3D object with no holes might be more visually appealing to look at, introducing algorithms to fill these holes will make conjecture unavoidable.

The issue with the current proposed standard parameters and workflows referenced in this review is that they are not quantifiable to the degree of being objective. As such, different researchers, producers, and curators will weigh them differently based on their needs, and a unified and reproducible metric for all forms of 3D data is unachievable.

Standardized formats and their use

Specialized production also often results in data formats that supports the primary objective of each specific data acquisition process, possibly limiting the interoperability or applied use of the approach for other means. A few papers and projects investigate the creation of evaluation datasets, but this approach has yet to see too much development in the field. Using such tools, different approaches could tested on the same object which might give a better baseline evaluation of an applied methodology or processing technique.

Tools like the H3D dataset from [74] released in 2021 is an example of how it might be useful for researchers and developers to test out their new processing workflows, and quantitatively compare them to others who have used the same dataset. H3D is a UAV LiDAR dataset depicting the town of Hessigheim, Germany in several epochs, and terrestrial data acquired by UAV LiDAR are often used for researching heritage sites and buildings[75–77]. The work has 32 citations at the time of writing, and note that this is not a collectively approved standard. Other examples of such datasets include CO3D [78] from Meta, HM3D [79] and LIBRE [80]. Similarly there is no such baseline for smaller type objects. While the Stanford Bunny [81] has been used for a long time for such applications, it has never been universally recognized as an evaluation tool. Its age is also becoming apparent from a technological perspective, as modern acquisition methods are able to acquire 3D data at a higher rate and density. Issues with utilizing such baseline datasets for method evaluation is that they are also

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[70] https://www.myminifactory.com/scantheworld/

unavoidably affected by the original acquisition method and tools, but for the sake of method testing this might be disregarded. Merit of 3D CH data is yet another discussion that is outside the scope of this review, but an interesting note is the difference between reality-based data, born-digital data, and processed reality-based data. Prior papers have investigated this [82–86], but there are still many ethical dilemmas with 3D CH to consider.

While differences in the structures of file formats are also out of the scope of this review, it defines the readability of the data by different software and viewing platforms. Therefore being the first step in interoperability. The European Commission's latest report provides a comprehensive list of current 3D formats, rasters, and vectors, along with international standardization bodies.[71] We note the vast amount of formats, along with how many are listed as standards for different industries. Institutions that are currently working on standardization on 3D CH data are the European Committee for Standardzation,[72] International Organization for Standardization,[73] and the Web 3D Consortium.[74]

Digital platforms and APIs

Most of the data collectors and data repositories that feature web-viewing of their content integrate other 3D viewers in their websites with a provided API. An API is an intermediary software which allows different applications to "talk" to each other. The EU Project 3D Icons [65] provide some considerations for choosing publishing platforms, building on results from the CARARE project [87]. Their evaluation mostly orients around user friendliness, and technical specifications for the data is very limited. This is very similar to the reviewed projects and workflows mentioned earlier. But there are several other ways to visualize 3D CH data digitally, ranging from Javascript frameworks to game engines.

There are a lot of digital services for hosting and visualizing 3D models, but they should not necessarily be all counted as fit for visualizing CH research. Some that are often mentioned in previous reports to possibly visualize 3D CH data are Sketchfab,[75] Hexagon,[76] Configure One,[77] Atlatl,[78] Soft8Soft,[79] 3D Cloud Marxent,[80] CanvasLogic,[81] Threekit,[82] ModelViewer,[83] p3d,[84] 3DHop [88], PoTree,[85] Exhibit,[86] Mozilla,[87] SayDuck,[88] Kompakkt,[89] GB3D,[90] Universal Viewer,[91] Smithsonian Voyager,[92] ADS 3D Viewer,[93] and ATON Framework[89]. Note that some of these are designed for a specific project, and are therefore tailored-made for the project requirements. Others are designed for specific formats of 3D data, like PoTree being designed for rendering of large point clouds and Universal Viewer specifically supporting 3D viewing of IIIF manifests. But more importantly, many of these often cited 3D viewers are designed for product visualization for commercial businesses, and are therefore not designed or applicable for 3D CH data. Requirements like the ones mentioned prior are either limited or nonexistent, limiting the viewing to extremely simplified 3D objects with restricted inspection. While Sketchfab is in the lead in terms of users and uploads, and is indeed a popular upload platform for CH projects, it is also primarily designed for visualizing and interacting with simple 3D objects at a commercial/audience level. Like most of these viewers, it is not a platform servicing quantitative research approaches to the data they host. In Table 3 and 4, we have provided an overview of the features of the different 3D viewers. Features that are covered include general attributes like "Cost", "PBR Rendering", and "Object Statistics Inspection" which reports object information like vertex and polygon numbers. Features more specifically relevant to the CH field, like "Measuring Tool" and "Peer Review" are also covered. Authenticity also becomes an issue when visualizing creative and research-based data in the same viewer. This is apparent in the large collection of 3D objects classified as CH on the Sketchfab website, where many of the objects are custom made replicas of a CH object.[94] This is an important

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[71] https://digital-strategy.ec.europa.eu/en/library/study-quality-3d-digitisation-tangible-cultural-heritage/

[72] https://www.cencenelec.eu/

[73] https://www.iso.org/home.html

[74] https://www.web3d.org/

[75] https://sketchfab.com/

[76] https://hexagon.com/products/product-groups/3d-design-visualisation

[77] https://www.configureone.com/

[78] https://www.atlatl.com/

[79] https://www.soft8soft.com/verge3d/

[80] https://www.marxentlabs.com/

[81] https://canvaslogic.de/en/

[82] https://www.threekit.com/

[83] https://modelviewer.dev/

[84] https://p3d.in/

[85] https://potree.github.io/

[86] https://www.exhibit.so/

[87] https://hubs.mozilla.com/

[88] https://www.sayduck.com/

[89] https://kompakkt.de/home

[90] http://www.3d-fossils.ac.uk/home.html

[91] https://universalviewer.io/

[92] https://smithsonian.github.io/dpo-voyager/

[93] https://archaeologydataservice.ac.uk/archives/view/lascuevas_uchn_2016/viewer.html

[94] https://sketchfab.com/nebulousflynn/collections/cultural-heritage-and-history-top-10-2023-wk-2-09db3832251744979776 88f04d1d27ac

Table 3 3D viewer features 1–12

Nr.	1	2	3	4	5	6	7	8	9	10	11	12
Name	3D Cloud Marxent	3DHop	3DViewer	ADS 3D Viewer	Aleph	Atlatl	ATON Framework	CanvasLogic	Clara.io	Configure One	Exhibit	GB3D
Free Cost	×	✓	✓	✓	✓	×	✓	×	✓	×	✓	✓
Open Source	×	✓	✓	✓	✓	×	✓	×	×	×	v	×
LOD Support	×	✓	×	✓	×	×	✓	×	×	×	×	×
PBR Rendering	×	×	✓	×	×	×	✓	×	×	×	×	×
Object Statistics Inspection	✓	×	✓	×	✓	×	✓	✓	✓	×	✓	×
Direct Download	×	×	✓	×	✓	×	×	×	✓	×	✓	✓
Annotation	✓	✓	×	✓	✓	×	✓	✓	×	✓	✓	✓
Cross Section	×	✓	×	✓	✓	×	×	×	×	×	×	×
Point Cloud	×	×	×	×	×	×	✓	×	×	×	✓	×
Peer Review	×	×	×	×	×	×	×	×	×	×	×	×
UV Inspection	×	×	×	×	×	×	×	×	×	×	×	×
VR / AR Support	✓	×	×	×	×	✓	✓	✓	×	✓	×	×
Lighting Change	✓	✓	×	✓	×	✓	✓	✓	×	×	×	×
HDRI Lighting	×	×	×	×	×	×	×	×	✓	×	×	×
Measuring Tool	✓	✓	✓	✓	✓	✓	×	✓	×	✓	×	×
Scripting	×	×	×	×	✓	×	×	×	×	×	×	×
Screenshots	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Animation	✓	✓	×	✓	✓	✓	×	✓	×	✓	✓	×
Particle Systems	×	×	×	×	×	×	×	×	×	×	×	×
Sound	×	×	×	×	×	×	×	×	×	×	✓	×
Multi View	✓	✓	✓	✓	×	✓	✓	✓		✓	✓	×
Heritage Specific	×	✓	×	✓	×	×	✓	×	×	×	✓	✓

Table 4 3D Viewer Features 13–24

Nr.	13	14	15	16	17	18	19	20	21	22	23	24
Name	Hexagon	Kompakkt	Modelviewer	Mozilla	p3d	PoTree	SayDuck	Sketchfab	Smithsonian Voyager	Soft8Soft (Verge3D)	Threekit	Unive rsal Viewer
Free Cost	×	✓	✓	×	✓	✓	×		✓	×	×	✓
Open Source	×	✓	✓	×	×	✓	×	×	✓	×	×	✓
LOD Support	×	×	×	×	×	✓	×	×	×	×	×	×
PBR Rendering	×	×	×	×	✓	×	×	✓	✓	✓	×	×
Object Statistics Inspection	✓	×	×	×	✓	✓	✓	✓	✓	×	✓	✓
Direct Download	×	✓	×	×	✓	×	×	✓	✓	×	×	✓
Annotation	✓	✓	×	×	✓	✓	✓	✓	✓	×	✓	✓
Cross Section	✓	×	×	×	×	✓	×	×	✓	×	×	×
Point Cloud	✓	×	×	×	×	✓	×	✓	×	×	×	✓
Peer Review	×	×	×	×	×	×	×	×	×	×	×	×
UV Inspection	×	×	×	×	✓	×	×	✓	×	×	×	×
VR / AR Support	×	×	✓	✓	✓	×	✓	✓	×	×	✓	×
Lighting Change	✓	×	×	✓	✓	×	✓	✓	✓	×	✓	×
HDRI Lighting	×	×	×	×	✓	✓	×	✓	×	✓	×	×
Measuring Tool	✓	×	×	×	✓	✓	✓	✓	✓	✓	✓	×
Scripting	✓	×	×	×	×	×	×	×	×	✓	×	×
Screenshots	✓	×	×	✓	✓	✓	✓	✓	✓	✓	✓	✓
Animation	×	×	×	✓	✓	×	✓	✓	×	✓	✓	✓
Particle Systems	✓	×	×	×	×	×	×	✓	×	×	×	×
Sound	×	×	×	✓	✓	×	×	✓	×	✓	×	✓
Multi View	✓	×	×	✓	✓	✓	✓	×	×	✓	✓	✓
Heritage Specific	×	×	×	×	×	×	×	×	×	×	×	✓

categorical difference that the field needs to consider moving forward, to achieve the differentiation from computer graphics mentioned by Pfarr-Harfst. Standardization frameworks like IIIF might be a tool to enrich the functionality of viewing 3D objects on the web, and serve as an authentication factor for digital objects. But implementation of the framework is still limited for the moment, and must implement a lot of desired tools to be useful for research purposes. Nonetheless, it shows promise for a verifiable approach for visualizing research data in 3D viewers in the future.

But, there are some current viewers that are specifically designed for more interaction and scientific approaches, like ATON Frameworks[89] multi-temporal visualization, Visual Media Service's RTI relighting features [90], and CHER-OBs analysis tools[91]. 3D viewers like these should be adopted by the CH/computer science field to step away from the commercial and creative environments like Sketchfab. Another online 3D viewing platform that is research based is Virtual Interiors. A partner program led by Huygens Institute for the History of the Netherlands, Virtual Interiors seeks to visualize interiors from the Dutch Golden Age based on historical data, which can then further be used in culture development and creative productions [92]. Developed with BabylonJS JavaScript framework, the project seeks create a platform for reading and visualizing Big Data on the web. Such frameworks provide blueprints for 3D implementation on the web, and are more customizable ways of integrating quantitative investigation of 3D CH data to a website compared to an API. Albeit with the trade-off of longer development time and specialized implementation. Other JavaScript frameworks that could be used for similar purposes are Three.js, D3, Aframe, Cannon.js, and PlayCanvas. These frameworks includes some baseline 3D format loaders, but has support for adding additional loaders as well. Note that not all 3D formats are supported.[95]

Such frameworks are more flexible than online 3D viewers, as it opens for institutions to develop custom tools for their own purposes while using universal formats. The Vasa Museum for example uses WebGL for their internal database Vasabas,[96] which includes a multi-temporal visualization built in to the software. But such custom software may also make it harder to share content that is developed in-house, as the frameworks include a lot of dependencies. Programming interfaces like OpenGL, HTML 5, Mesa, and Vulkan provide similar tools. While these frameworks provide more flexibility than out-of-the-box 3D viewers, they still struggle with large scale datasets or 3D objects of high resolution, of which there are many in 3D CH depositories. For this, more heavy duty software might be required.

Game Engines like Unreal Engine and Unity are tools for constructing larger scale visualizations of 3D objects, and due to their industrial production purpose they feature some of the most effective and powerful tools for large-scale projects. Especially one of the new features of Unreal Engine, a geometry decimation system called Nanite[97] shows great promise for visualizing high-resolution 3D objects in real time without too much performance loss. But, utilization of such systems requires the software to be built within the game engine framework, which may currently have limited out-of-the-box support for quantifiable 3D analysis of CH. It also limits its connectivity to the web, restricting the software to only utilize files stored locally on the system. But, both Unity and Unreal Engine has extended the possible applications for their frameworks beyond the video game industry. Especially implementations in the fields of architecture, automotive, virtual productions,[98] and the metaverse[99] displays the flexibility of these engines. Little then stands in the way of developing such tools towards 3D CH applications in the future, and foundations like The Linux Foundation[100] and the Open 3D Foundation[101] consist of large actors within the 3D field that work towards open-source developments.

Discussion

Through this review, we have found that several of the original theorized applications for 3D in CH have been explored in various ways, as different projects implements 3D for CH for means of education, dissemination, and simulation. Visualization seems to still be the primary result of many of these projects, either for the purpose of visualizing to an audience or exploring different data acquisition methodologies. But in many ways the various projects remain fragmented and isolated from each other. Ad hoc solutions for implementation mirrors the ad hoc acquisition workflows of data collectors, making it almost impossible to quantitatively compare two similar implementations by the same parameters.

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[95] https://github.com/mrdoob/three.js/tree/dev/examples/jsm/loaders

[96] https://sketchfab.com/blogs/community/vasa-national-maritime-museum/

[97] https://docs.unrealengine.com/5.0/en-US/nanite-virtualized-geometry-in-unreal-engine/

[98] https://www.unrealengine.com/en-US, https://unity.com/

[99] https://metaverse-standards.org/news/press-releases/leading-standards-organizations-and-companies-unite-to-drive-open-metaverse-interoperability/

[100] https://www.linuxfoundation.org/

[101] https://o3d.foundation/

Evaluation of 3D project yields is therefore still very subjective in the CH field, as several root issues are yet to be tackled. In this review we have explored the most prominent and recurring issues with data acquisition, data storage, file formats, and standardization along with 3D object quality assessment, workflow variation, data actualisation, and limited research focus within the field of 3D in cultural heritage. It is clear that while there exist many great tools to aid and develop this process, there are still several shortcomings that are integral. Numeric evaluation tools on objective variables and statistics should be a priority for the field in the coming years, so that the variability of 3D could at least be quantified in the most recurring dimensions. Variables that we deem the most important for this are:

1. Geometric accuracy and its alterations and reductions in a 3D process.
2. 3D resolution levels utilized to digitize certain objects and surfaces, with distance measurements of whats captured within the resolution.
3. Processing power and computer memory required to utilize 3D objects.
4. Characterization of color and surface acquisition, and texture projection protocols.

Even though 3D can be used for a great variety of applications, and as a result will look significantly different within such measurements, it would be a tool for categorization and evaluation of 3D objects depending on the most important variables within its specific application. Subcategories would be created, that would narrow down the idea of 3D objects and what they include depending on the utilization. This could potentially lead to better standardization practices within each subcategory, and avoid the issue of attempting to develop a one-tool-fits-all standard.

While institutions would perhaps be more inclined to subscribe to agreed-upon standards, private enthusiasts of the general public might adhere to no such regulations. Public production is only set to increase in the future if the current trend continues, so it is vital for the research-field on 3D CH to separate 3D objects that artistically represents CH from research based 3D that attempts to visualize, archive, and analyze the truthful presentation of tangible CH objects. Development of standards would have to tackle a lot of different issues, as the heterogeneous and alterable nature of both CH and computer science will stretch and strain regulations in many different directions. First drafts would, and arguably should, therefore not encompass all variations, but attempt to establish some ground-rules based on the most recurring characteristics. The standardization is nonetheless vital for the research on the field, to be able to approach the data from a common scientific and quantifiable way. It would be the means to separate the generic visualization of computer graphics from the quantifiable research data of computer science, and elevate appearance acquisition and analysis for CH to a more concrete field. Variables of 3D implementations that are not part of an objects numerical evaluation that we suggest to pay more attention to are:

1. Extent of human intervention in the digitization process, compared to purely algorithmic.
2. Lifespan of the 3D object, both in terms of utilization and quality compared to current state-of-the-art.
3. Subsequent use of the 3D assets after initial acquisition and visualization.
4. Semantic and objective descriptions of the 3D asset and its use, instead of generic and open-ended.

Even with these suggestions, the field in relevance currently still very much depends on a lot of different actors from different backgrounds. Be it for interdisciplinary research or not. Researchers in this field must be aware of the interdisciplinary, commercial, public, and non-profit developments being made, as the public interactions with the research results is one of the primary objectives of 3D CH projects. As such, it would be beneficial to find some way to develop a workflow that does not narrow the 3D data acquisition to a specific research question or creative application, thereby making the data more universally relevant. Specialized training and education would allow for more nuanced and knowledgeable approaches, but the field is still too fragmented for such aspirations to emerge by themselves. A research gap for methods of validation and quality control of 3D objects is still prominent, especially in the CH sector where the conservation of object appearance, both shape and surface, is the main aspiration. If this is not considered by future projects, the heterogeneity of the field is only set to increase.

Europeana's controlled and organized approach to 3D data storage shows promise for a more officially-recognized standard, and similar institutions provide valuable input that gradually provides more guidelines for 3D data collectors. But still there is lacking some implementation to verify that their hosted objects are of a high quality. Suggestions of peer-reviews of uploaded 3D data is a very interesting notion that should be explored further, and attempt to develop a framework from which 3D models could be evaluated. Other quantitative approaches could also be made, like relating the tangible object's size or geometric variation to resolution requirements. We already have great quantities of 3D CH data available on the web, collected using various acquisition paradigms. Attempting to extract what research data we can from these pre-existing models would show us where they excel, where they fall short, and what characteristics are lacking for various research applications. Another project that is promising is the development of The European Collaborative Cloud for CH, which released its stakeholder survey in December 2022 [93]. This survey repeats a lot of what is noted in prior reports, and we hope that the development of this platform will take the shortcomings highlighted in this review into consideration.

One more segment that is seeing more development is the 3D viewing platforms. For a long time Sketchfab has reigned supreme as the 3D viewer of choice on the web, and while it offers some possibilities for 3D model inspection and provides a good API, we argue that it should not be deemed fit for hosting research-oriented 3D CH models apart from secondary-objective visualization. Some projects have opted for other 3D viewers that fits their format of 3D data, like PoTree, which comes with their own limitations or restrictions. General shortcomings of 3D viewers seems to be universal tools and format support, as well as object quality validation and embedding of metadata. While simpler tools like annotation is often listed as a feature of high priority, and is indeed implemented in most 3D viewers, the field should move towards using 3D viewers that opens more for processing of the dataset directly. Open Source projects have shown to provide good solutions for hosting 3D research data, and the transparency in development and code integration should be prioritized over proprietary, blackbox viewers.

Challenges and opportunities are apparent in every stage of a 3D project, from project planning to data implementation, and CH provide various challenges that strains creative workflows. Substantial work is being done in improving many of these stages, but we have highlighted a few that is key to elevating the research-field.

Conclusion

This review looks at different projects working with 3D CH data, including data collectors, data repositories, suggestions for standards and workflows, as well as viewing platforms and processing engines. We have highlighted some of the important developments in each segment, and proposed directions to where research should head into the future. There is no shortcoming of work being done, but we hope to see a bit more in depth application research in the future, as well as emphasis on research questions for 3D CH that is subsequent for acquisition.

The research field is an interdisciplinary field, and as such includes a great variation of competent institutions that could to contribute to standardization agreements, research, and development activities. However, in many cases the approach each institution selects is incompatible with the approach of another institution, limiting the interoperability of the implementation and reduces the possibility for sharing data directly. Current work shows great promise in providing solutions for these issues, but there is a lot of work still left to do.

Referenced 3D models

"Al Khazneh - The Treasury, Petra" (https://skfb.ly/6xBIP) by RaizNewMedia is licensed under Creative Commons Attribution (http://creativecommons.org/licenses/by/4.0/).

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"Lamasu - British Museum (Assyrian Collection)" (https://skfb.ly/6RJZz) by CyArk is licensed under Creative Commons Attribution (http://creativecommons.org/licenses/by/4.0/).

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Availability of data and materials
The paper presents and details all data used for the review. Additional access to the data are available upon request from the authors.

Declarations

Competing interests

The authors declare that they have no conflicts of interest in this work. We declare that we do not have any commerci al or associative interest that represents a competing interest in connection with the work submitted.

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