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Scanning of Historical Clothes Using 3D Scanners: Comparison of Goals, Tools, and Methods

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Abstract: Due to the UN and EU's strong interest in digitizing cultural heritage, the application of 3D scanning technology is gaining importance, even in the case of under-explored areas, such as the 3D scanning of historical clothes. This article discovers and compares methodologies of 3D scanning of historical clothes presented in the literature in order to determine if a new methodology is needed. PRISMA protocol was used to browse scientific sources in an organized way. We posed the following research question: How have 3D scanners been used to digitize historical clothes? The very limited number of works identified, despite our thorough search, allows us to conclude that this topic is very new, and a lot of research can be conducted in the future. We analyzed the methodologies proposed by other authors, taking into account factors such as what was scanned, what was the purpose of scanning, what hardware and software was used, how detailed the description was, etc. It was revealed that other authors explored the topic insufficiently and no complex and coherent methodology of 3D digitization of historical clothes is present. Generally, the field of 3D scanning of historical clothing remains, at this point, very small and fragmented. This work is one of steps to change it.

Keywords: 3D scanning; historical clothes; heritage digitization; methodology evaluation; systematic literature review

Citation: Żyła, K.; Kęsik, J.; Santos, F.; House, G. Scanning of Historical Clothes Using 3D Scanners: Comparison of Goals, Tools, and Methods. *Appl. Sci.* **2021**, *11*, 5588. https://doi.org/10.3390/app11125588

Academic Editor: Enrico Vezzetti

Received: 26 May 2021
Accepted: 11 June 2021
Published: 17 June 2021

1. Introduction

3D scanning in the field of cultural heritage involves computer science and cultural heritage preservation, resulting in the emergence of unique solutions. In this article we attempt to systematize and analyze the current state of knowledge about the digitization of historical clothes, which tend to be very delicate heritage artefacts, using 3D scanners.

1.1. Rationale

3D technologies are being used more widely in the area of cultural heritage each year. This holds true for museums that feel the need to make their exhibitions more attractive in the era of the digital society. Enabling access to museum collections for a wide audience by means of digital media has become relatively easy and has been successfully used not only by the world's leading museums but by smaller institutions as well [1–3].

However, the application of 3D scanning technology in digitization of cultural heritage objects is still a relatively young field; the methodologies are as yet under-developed, and knowledge about these techniques is not widespread [4]. One such under-explored area is the problem of the 3D scanning of historical clothes. Textiles are among the most perishable artefacts, but even the smallest fragments of textile are of value in understanding production technology and cultural significance [5,6].

Among museums with clothing in their collections, the most common methods of sharing resources in digital media are the presentation of 2D photographs [7], 360° photographic views [8], or 3D models made by means of very laborious CAD modeling [9] or photogrammetry. These techniques are used by a number of famous institutions, such as the Louvre in Paris, the V&A in London, the Kyoto Costume Institute in Japan, Google Arts & Culture platform, the Museum at FIT (MFIT), Drexel University's Historic Costume Collection, the Digital Clothing Center (DCC) at Seoul National University, and the Museum of London [10].

Within the academic literature, scientific studies on the topic of the 3D digitization of historical clothing tend to focus on the following areas:

- Building 3D models with CAD (Computer Aided Design) tools, either using dedicated software for clothes (such as CLO 3D, Gerber AccuMark 3D, Optitex or Lectra Modaris) or general modeling solutions (such as MeshLab, Blender 3D Creation Software, AutoDesk 3D, or Rhinoceros 3D);
- Construction of 3D models using photogrammetric techniques (3D model generation based on a series of photos of the object).

The above techniques are of limited accuracy when it comes to reproducing the shape and structure of garments. Greater precision and accuracy can be obtained using 3D scanners; however, only a small number of studies mention the use of 3D scanning in this process. Three-dimensional scanners, especially those based on structured light, provide a set of important features, especially with regards to obtaining a precise representation of the surface with simultaneous reproduction of its color. The value of these features is confirmed by the frequent use of this type of scanner in other aspects of the 3D digitization of cultural heritage objects. For these reasons, 3D scanners are the focus of the present study.

1.2. Three-Dimensional Digitization Technologies

Three-dimensional digitization of a real object can be understood as a process of translating the geometrical and visual features of the object's surface into a mathematical description. A 3D model can be perceived as a product of this process. Among the commonly used technological solutions for obtaining knowledge about these objects' features, we could mention the following:

1. CAD modeling;
2. Touch scanning;
3. Laser scanning;
4. Structured light scanning;
5. Computerized tomography scanning;
6. Photogrammetry.

CAD modeling might be perceived as a highly manual approach to producing a 3D model of a real object, in that a lot of human effort is needed to map the real object's geometrical and visual features to its 3D model. The other abovementioned solutions can be perceived as being more automated: they heavily utilize specialized algorithms that automatically recognize and reproduce the object's geometrical and visual properties in the form of a 3D model. The main disadvantage of CAD modeling, compared to the other mentioned solutions, becomes evident when the goal (and this is a very frequent one) is to obtain a 3D model offering an accurate representation of a real heritage object. More specifically, the disadvantage of CAD lies in the excess of freedom it provides in mapping the shape, such that the fidelity of the reconstruction can potentially be undermined. At the same time, striving to build a faithful model requires a significant amount of work and a high level of expertise from the creator. This type of approach is also used in heritage settings [11]; however, the resulting 3D model should be treated more as a representation of a given type of design than as a digital copy of a specific exhibit.

The touch scanning technology uses devices that have an arm with a probe that makes physical contact with the object. When the object is touched, the position of the probe is read, which allows the device to record the exact 3D position of a given point on the object's surface. If samples are collected densely enough, it is possible to recreate the shape of the object with the required accuracy. However, exposing a fragile cultural heritage object to repeated contact with a hard probe risks potential damage. Although the accuracy of the obtained surface measurements is high, scanning by touching the surface of the object so as to reproduce every detail is extremely burdensome, and in some cases, even impossible. A further disadvantage of this solution is that no information is obtained regarding the color of the scanned surface.

In laser scanning devices, the physical probe has been replaced with a laser beam. The device directs the beam to a specific point in space and captures the returning beam reflected from the object's surface. On the basis of the reflected beam's parameters, the distance to the reflection point can be calculated, indicating the position of a given surface point in space. Modern scanners also have an integrated camera that allows the colors to be read and matched at the designated 3D points. Modern scanners use Class 1 lasers operating in the infrared light band. Therefore, they do not adversely affect the surface of the scanned objects, unless it is particularly sensitive. Most often, scanners of this type provide a large scanning range and accuracy expressed in millimeters, and they are used to scan large cultural heritage objects (vehicles, buildings, and even entire historical sites) [12–16].

Structured light scanning involves devices that project an image onto the scanned object. The scanner projector displays an image containing a certain structure (most often fringes of different widths). The distortions of the fringes formed as the projection falls on the three-dimensional surface of the scanned object are captured by cameras that have been calibrated with the projector. The differences between the original and the captured image are used to calculate the topography of the object's surface in 3D. It is also possible to obtain the color of the object's surface, along with its 3D shape. Structured light scanners can be stationary (i.e., the scanning head is stationary and the scanned object is moved) or mobile (the scanning head is movable, often handheld, while the scanned object remains stationary). It is possible to scan objects of various sizes, from a few millimeters to several meters, to an accuracy of fractions of a millimeter, depending on the device.

Computerized tomography (CT) scanning technology is more widely used in medicine; in fact, most descriptions of the use of CT scanning in the area of cultural heritage indicate the use of devices intended for medical purposes. The operation involves the construction of a 3D model based on a series of X-ray images of the object. In the area of cultural heritage, it has a narrow set of applications, where the goal is not so much to obtain a model of the surface of the object but to visualize its interior using non-invasive methods.

The photogrammetry solution comes from the GIS (Geographic Information System) field, where it is used to determine the topography of a landscape based on aerial photographs. To digitize an object in this way, it is necessary to acquire a significant number of surface images (for example, photos taken with ordinary digital cameras) covering overlapping areas. Dedicated software finds easily distinguishable points in each image and then matches the equivalents in different images. On this basis, the position of these points in 3D space can be determined. The physical scale of the scanned object cannot be ascertained directly from images, thus obtaining the correct size of an object requires additional determination of its scale, for example, by means of a calibration object placed next to the scanned object. In the area of cultural heritage, photogrammetry is used in 3D modeling of both small exhibits and larger areas, such as archaeological sites or buildings. In most descriptions of scanning methods, photogrammetry is seen as a separate technique, and is not classified as 3D scanning. For the purposes of this article, it is included, but at arm's length, as it were, to highlight the ambiguous or erroneous use of the term "3D scanning" in the literature.

1.3. Objectives

Thus far, very few publications have been devoted to the scanning of historical clothes using 3D scanners. To the best of our knowledge, the full potential of 3D scanners is not being exploited in this particular field. This situation prompted us to ask whether any scientific approach to this topic has been developed. The usefulness of specific technological solutions and methods can be properly confirmed by asking whether their application is discussed in the form of scientific studies, and whether there are any academics tackling the complex question of a methodology for scanning clothing—a highly diversified category manifested in a huge variety of different shapes (from shoes to hats) and materials (from linen to golden threads reflecting scanner light). We also wished to explore whether any methodology for analyzing results has been developed.

To investigate this, we started from the following research question:

RQ: "How have 3D scanners been used to digitize historical clothes?"

To answer this question, we defined the following research objectives:

RO1: Identify whether studies on this topic exist and how many there are.

RO2: Identify the purpose driving the creation of 3D scans and the technology used.

RO3: Assess how well the literature describes the 3D scanning procedure.

2. Research Methodology

We chose to put discovery and analysis of methodologies of 3D scanning of historical clothes in the frames of well-established protocol, which is generally advised in the literature, e.g., by Reference [17]. We followed the procedure outlined in the PRISMA-P 2015 protocol, a revised and improved version of PRISMA 2009 [18] that has been widely adopted by the scientific community [19,20]. We found the protocol useful in organizing our search, and defining criteria and procedure of the methodologies evaluation and comparison.

2.1. Eligibility Criteria

Our goal was to select studies with relation to the 3D scanning of historical clothes using dedicated professional devices called 3D scanners. We did not investigate studies on the creation of 3D models from photographs taken, for example, by DSLR cameras or iPhone devices. As such, this article deliberately excludes many valuable studies about photogrammetry usage for digitizing historical clothes.

2.1.1. Inclusion Criteria

We selected studies that do the following:

1. Relate to the 3D scanning of historical clothes using 3D scanners;
2. Provide any details on the procedure of 3D scanning of clothes, or any proof (pictures, descriptions, models, etc.) of the 3D scanning of clothes.

We defined historical clothes as any kind of clothing (for humans or even for dolls) that are considered heritage items (according to the authors of the analyzed studies); are part of a private collection of historic value; or form part of a museum's collection. Photogrammetry was outside scope of our search criteria, although studies that referred to photogrammetry "as 3D scanning" were included into the analysis as an example of imprecise usage of terminology by authors. Finally, only scientific sources were included in the scope of the analysis, such as peer reviewed journals, conference proceedings, books, book chapters, and theses (undergraduate, master's, and doctoral) if returned by queries run in the chosen databases. We were able to access the full text of all studies included into the analysis, encountering no problem with paywalls. No limits were placed on publication dates in our search terms.

2.1.2. Exclusion Criteria

We excluded the following:

1. Studies containing the query keywords that were not related to the 3D scanning of historical clothes;
2. Studies about the 3D scanning of jewellery, having previously agreed that jewellery should not be considered clothing but treated as an accessory;
3. Studies that only mention that clothes are a type of heritage item that could be 3D scanned but provide no details whatsoever on procedure of scanning clothes, present no examples (pictures, descriptions, and models) of 3D-scanned clothing, and offer no background information on clothes. Knowing the background of clothes is essential to determining whether an item of clothing can be assumed to be historical.

We used English keywords in our bibliographic database queries, based on the assertion that English is the common language of modern science. As a result, we may have excluded some less visible studies written in other languages and with no English-language abstract or keywords. Some databases returned results in other languages, such as German, French or Dutch, even though the queries were in English. Thankfully, our team had sufficient skills in these languages that we could carry out the screening process on these studies.

2.2. Information Sources

The academic databases considered for this review were ACM, IEEE (two main engineering professional associations), Scopus, Web of Science, Wiley, Springer, and ScienceDirect (main publishers of academic studies). All of these databases index conference proceedings and journals that are considered reputable and of good quality.

We also expanded our query to Google Scholar to ensure a more complete coverage of the topic (accounting for variability between the indexing in each database). Using Google's academic engine has some advantages, as it detects works of lower visibility that have been archived in more informal repositories such as academic social networks (for example, ResearchGate and Academia.edu).

2.3. Search Strategy

The search was conducted on 22 February 2021. The keywords used in the query string executed for each chosen bibliographic database were derived from the research question.

The keyword summary can be found in Table 1. We decided to search for the formal synonyms of the word "clothes" according to the online Cambridge English Dictionary (https://dictionary.cambridge.org/pl/dictionary/english/clothes). The list was further expanded with other words that the authors knew from experience might occur in scientific sources in the context of the 3D scanning of clothes, namely "garment", "costume", "fashion", "textile", and "outfit". Another element of the query was technology-related—keywords which reflect the activity of 3D scanning, its results, and devices used for such purpose, i.e., 3D scanners. Finally, since this study focuses on historical clothes, the keywords included variations of the words "historic", "heritage", "museum", and "old".

Some of the keywords were quite generic and widely used in areas other than the digitization of clothes; for example, a large number of irrelevant results were generated from the fields of medicine and materials engineering. We included such terms intentionally, as we already knew that the set of relevant studies would be quite small, thus we needed our query to be broad enough that nothing relevant would be missed.

Based on the query keywords summary, the following representative query was built: ("3D scan*") AND (histor* OR heritage OR muse* OR old*) AND (clothes OR clothing OR fashion OR textile* OR costume* OR apparel* OR garment* OR dress* OR outfit* OR attire*).

Table 1. Query keywords.

Word	Reason	Wildcards
clothes, clothing, apparel, dress, attire	Formal synonyms of "clothes" (according to the Cambridge English Dictionary)	Asterisk (*)—to include, when possible, both singular and plural form
garment	A piece of clothing	
costume	A frequent synonym of historical clothes	
fashion	A style that is popular at a particular time, especially in clothes, hair, make-up, etc.	
textile	Cloth made by hand or machine in large quantities	
outfit	A set of clothes worn for a particular occasion or activity	
3D scanning	Reflects the activity of 3D scanning	Asterisk (*)—to include a variety of tense forms
3D scan	Reflects the result of 3D scanning	Asterisk (*)—to include a singular and plural form
3D scanner	Reflects the use of 3D scanner	
history	Reflects the historical nature of clothes	Asterisk (*)—to include all variations of the word
museum	Historical clothes might be managed by a museum	
heritage	Historical clothes might be called an aspect of heritage	Asterisk (*)—to include other forms of the word
old	Historical clothes might be called old	

The query assumes the following:

1. Wildcards inside of quotation marks are interpretable;
2. An asterisk (*) represents a string of zero or more characters;
3. The words inside quotation marks should be in the provided order in the text;
4. "AND" and "OR" are logical operators;
5. Parentheses group logical expressions.

The representative query was then adjusted to each of chosen databases, to meet the specific criteria of each search engine. We tried our best to ensure the same meaning of the query each time. Not all of chosen search engines provided full control over the query interpretation; for example, ScienceDirect handled variations of keywords, such as different tenses for scanning activity verbs, or plural and singular forms, but did not allow wildcards and only allowed a limited number of keywords. In case of severe limitations on numbers of keywords or use of wildcards, we split our query into many smaller ones to preserve its original coverage, removing duplicated results if necessary. Thankfully we were able to obtain comparable interpretations (or a wider interpretation, as with Google Scholar) of the representative query in each of the chosen databases, which suggests that in each case we searched for all the necessary keywords variations.

In each database we chose the search type according to the following criteria: (1) keywords+abstract+title and (2) full text search if possible. The scope of each search was set to the broadest possible, in order to ensure that all possible sources of studies were included, with no date-of-publication limits, no discipline or topic excluded, no study type excluded, and so on. The number of query results and the search type for each database used is presented in Table 2. The search type names from the table comply with the names used by particular databases.

Table 2. Query results.

Database	Search Type	No. Studies
ACM Digital Library	Anywhere	332
IEEE Xplore	All metadata and full text	405
Scopus	Title–abstract–keywords	20
Web of Science	Topic search	22
Wiley Online Library	Anywhere	558
Springer Link	Anywhere	1050
ScienceDirect	Anywhere	558
Google Scholar	Anywhere	~9770 *

* Google scholar returned information that about 9770 results were found. However, the search engine was constructed in such a way that it only displayed 1000 results returned as the "most relevant".

2.4. Study Records

2.4.1. Selection Process

We identified a total of 2945 studies that originated from the high-quality bibliographic databases (ACM Digital Library, IEEE Xplore, Scopus, Web of Science, Wiley Online Library, Springer Link, and ScienceDirect). A further 46 records were identified via Google Scholar. We identified 66 duplicates among all the records. After removing these, 2879 records underwent the screening phase in which the eligibility criteria were applied. Only 12 studies were found eligible and were included in the subsequent qualitative and quantitative analysis. For details see the PRISMA flow diagram in Figure 1.

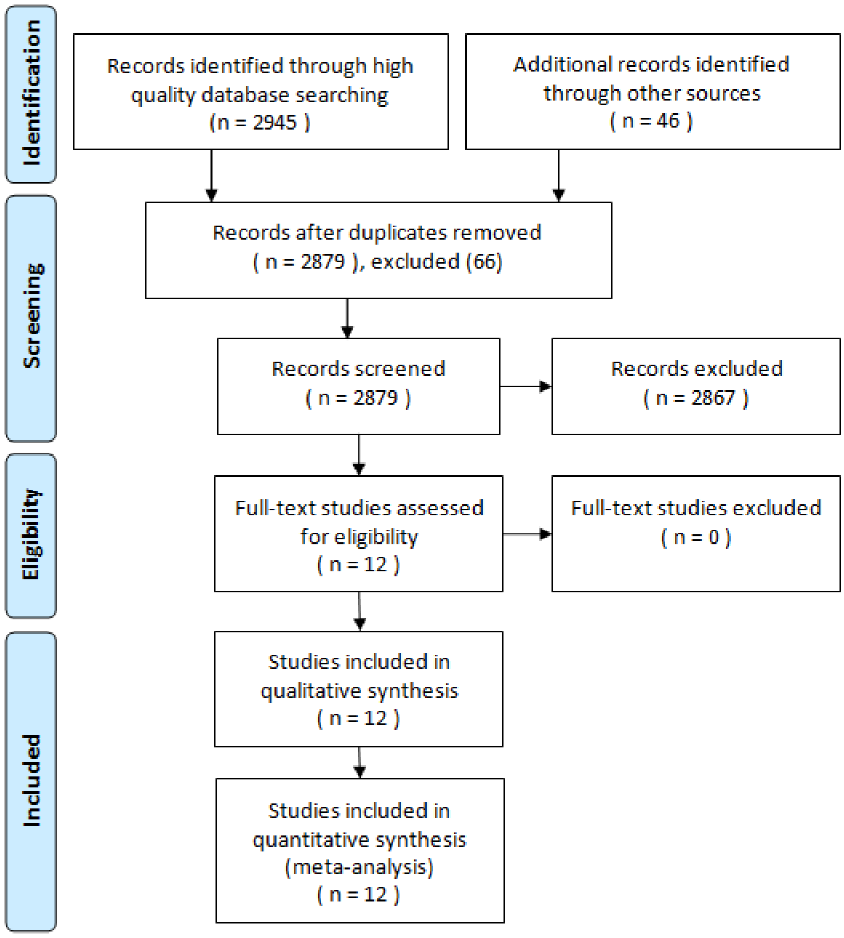


Figure 1. PRISMA flow diagram.

We decided to process the results from Google Scholar separately, as we perceive this source as less of a high-quality bibliographic database. Moreover, it presents too many significant technical problems when it comes to applying the PRISMA protocol steps in the same way as was achieved for records from other chosen databases. Google Scholar is not designed for literature reviews; some of issues, among others, include imprecise output (for example, estimated number of results, a limit of 1000 records shown); non-transparent search algorithms; and insufficient support for bibliometric analysis and deduplication. Nevertheless, it is a source of records for studies not indexed in the other databases which might nevertheless be relevant for our review. Thus, we decided to briefly analyze the records returned by Google Scholar, choosing any that looked relevant and creating a list that could be included in the PRISMA-P workflow as additional records identified through other sources. This was performed independently by two of the authors (Żyła and Kęsik).

The same two authors independently screened the titles and abstracts yielded by the search against the inclusion criteria to reduce the possibility of excluding relevant reports. Discrepancies were resolved through an inter-rater agreement. Full studies that appeared to meet the inclusion criteria were extracted, as were those where there was any uncertainty. The two reviewers then screened the full study and decided whether it met the inclusion criteria. Disagreements were solved through discussion, and the reasons for excluding studies were documented.

2.4.2. Data Management

Due to the relatively small number of studies that were eligible for inclusion in this study (n = 12), we used the more traditional form of data management, namely the online spreadsheet software Google Sheets. Because it was accessible online, this spreadsheet served as a collaborative tool, allowing the three authors to discuss and arrive at a consensus on issues of quality assessment.

In order to compute the statistics and manage duplicates, we developed our own software which took text files generated by bibliographic databases in CSV or BibTex format as an input. The metadata of studies was extracted (DOI numbers, titles, etc.) and compared accordingly. The comparisons were made in a case insensitive manner, whenever appropriate.

2.4.3. Data Collection Process

To ensure consistency between the two reviewers (Żyła and Kęsik), calibration exercises were undertaken before the review. Disagreements were solved through discussion, and one arbitrator (Santos) adjudicated on unresolved disagreements. It was decided to contact study's authors if any uncertainties remained.

2.5. Data Items

The thorough qualitative and quantitative analysis of the selected studies required a precise and uniform set of data to be extracted in each case. The kind of data that was extracted and categorized according to the particular research objective is presented in Table 3.

Table 3. Data items to be extracted from the studies.

Research Question: How Have 3D Scanners Been Used to Digitize Historical Clothes?	
Research Objective	**Data Items**
RO1: Identify whether studies on this topic exist and how many there are	• The source of study (e.g., bibliographic database name) • The authors' data • Type of publication • Keywords

Table 3. *Cont.*

Research Question: How Have 3D Scanners Been Used to Digitize Historical Clothes?	
Research Objective	**Data Items**
RO2: Identify the purpose driving the creation of 3D scans and the technology used	• Scanner type/technology type used for scanning • Purpose of 3D scan/reason for scanning • What was scanned
RO3: Assess how well the literature describes the 3D scanning procedure	Hardware and software (equipment): How well is the hardware and software described? • Procedure: How well is the procedure described? • Objects: How well are the scanned objects described? • Guidelines: Is the paper focused on giving guidelines?

2.6. Risk of Bias in Individual Studies

The PRISMA-P protocol encourages careful thinking in anticipation of possible bias (or risk of bias) in the analyzed studies. It encourages authors to make a clear distinction between the "quality of a study" and the "bias of a study" in the following way [18]:

Quality is often the best the authors have been able to do. For example, authors may report the results of surgical trials in which blinding of the outcome assessors was not part of the trial's conduct. Even though this may have been the best methodology the researchers were able to do, there are still theoretical grounds for believing that the study was susceptible to (risk of) bias.

We can argue that the quality of 3D scans of clothes is very much the result of the characteristics of the equipment used for the scan, the characteristics of the item that was scanned (for example, whether has a shiny surface, if it is unmovable) and the overall setup characteristics (such as light conditions). A failure to explain these characteristics in detail could be seen as introducing bias in the results. However, since our research question concerns the issue of how have scanners been used, rather than how successfully they have been used, we find that failing to properly document the characteristics of the setup is a problem of the quality of the study rather than bias in the study.

2.7. Data Synthesis

RO1 and RO2 were answered by means of quantitative statistical analysis of each variable taken into consideration (see Table 3). All studies were considered in the analysis.

RO3 has a more qualitative nature, aiming to assess the "quality of the study" according to the classification given by reviewers who are experts in the field. This quality analysis was undertaken according to four dimensions:

1. Hardware and software: How well was the hardware and software described?
2. Procedure: How well was the procedure described (e.g., light, scanner settings, and how to use the equipment)?
3. Objects: How well did the authors describe the objects that were scanned and their historical context?
4. Guidelines: Did the authors offer guidelines for people who would like to scan objects similar to those presented?

From this, our methodology for data synthesis was as follows:

1. Each of the selected studies were independently evaluated (reviewed) by Żyła, Kęsik and Santos in terms of these four dimensions.

2. For the dimensions of hardware and software, procedure, and objects, a Likert Scale was used with five categories: (1) not described, (2) partly described, (3) moderately described, (4) very well described, and (5) completely described.
3. The guidelines dimension was evaluated using a binary scale (1 = yes, 0 = no).
4. The assessments of the three reviewers were then aggregated by an average mean on each of the three first dimensions (hardware and software, procedure, and objects). We decided that the guidelines dimension should not be used in assessing the quality of the study, as this variable was mainly created to identify whether or not guidelines are frequently offered in the studies.
5. Finally, the three reviewers discussed any instances of very different item assessments between them. The final decision was reached by consensus.

The final outcome—an assessment of the general quality of each study—was reached by taking the average mean of the aggregated mean values of the three dimensions that were used to assess quality.

2.8. Comments on the PRISMA Protocol

The following elements of PRISMA protocol were not addressed: outcomes and prioritization, meta-bias(es), and confidence in cumulative evidence. We found them to be outside the scope of our article, due to the topic of study, the available data, and the character of the research objectives.

3. Results

The full list of studies that we found eligible for further analysis can be found in Table 4. We decided to assign a special ID that would be used to identify a study in the following sections using a simple code. Another code we introduced in the table concerns the type of study: CP—Conference Proceeding and JP—Journal Paper. In the following section, we analyze the studies in context of our research objectives.

Table 4. Full list of eligible studies.

No.	ID	Source	Title	Author	Study Type	Year
1	AC18	ACM Digital Library	Object-focused mixed reality storytelling: technology-driven content creation and dissemination for engaging user experiences	Darzentas et al. [21]	CP	2018
2	IE20	IEEE Xplore	Manipulating puppets in VR	Nitsche and McBride [22]	CP	2020
3	IE01	IEEE Xplore	Super high resolution 3D imaging and efficient visualization	Basu and Cheng [23]	CP	2001
4	SC14	Scopus	Reconstructing textile heritage	Calvert et al. [24]	JP	2014
5	SP18	Springer Link	3D visualization of a woman's folk costume	Kočevar et al. [11]	JP	2018
6	GS19a	Google Scholar	Future applications of digital clothing for historical costume: the past, present and future of fashion	McNulty [25]	CP	2019
7	GS19b	Google Scholar	Thickness mapping of body armor: a comparative study of eight breastplates from the National Museum of Slovenia	Lazar and Kraner [26]	JP	2019
8	GS18	Google Scholar	3D technology in collaborative heritage preservation	DeHass and Taitt [27]	JP	2018
9	GS17	Google Scholar	3D scanning and 3D printing technologies used in Albanian heritage preservation	Tota et al. [28]	JP	2017
10	GS16	Google Scholar	Use of image based modeling for documentation of intricately shaped objects	Marčiš et al. [29]	JP	2016
11	GS13	Google Scholar	Enhancing the display of the fashion artefact through digital multi-media approaches	Capacete-Caballero et al. [30]	CP	2013
12	GS12	Google Scholar	3D modeling of cultural objects in the V&A Museum: tools and workflow developments	Stevenson et al. [31]	JP	2012

3.1. Answer to Research Objective 1

To answer Research Objective 1 (RO1: Identify whether studies on this topic exist and how many there are) we conducted a bibliometric analysis on the selected studies. In general, a bibliometric analysis assumes that each field of study can be described by using significant information collected from the metadata of the literature published in that field, such as authors, keywords, terms from titles and abstracts, citations, and references [32].

We began by analyzing the frequency of published studies by year and by type (whether if it was published in a conference proceeding or a journal). Figures 2 and 3 show the results. In average one study per year was published starting from 2012. Only 1 of 12 studies was published before 2012—a technology (a laser scanner) showcase from 2001. Most studies (7 of 12) were published in journals, the rest in conference proceedings. Google Scholar was the source for seven works that were not indexed by the high-quality bibliographic databases.

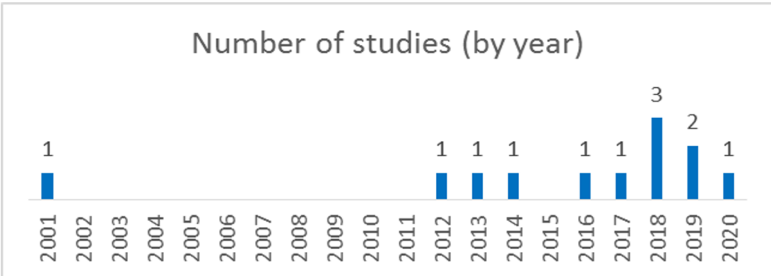
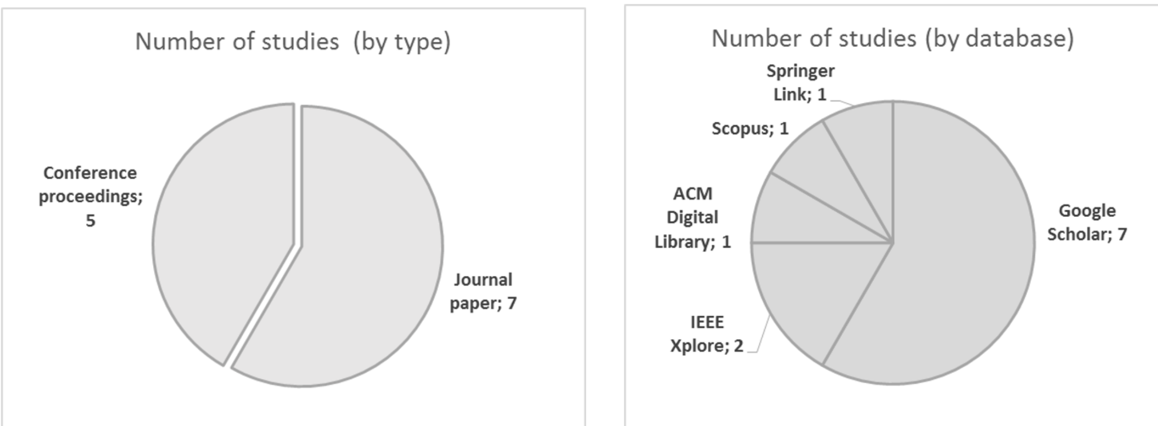


Figure 2. Number of studies by year.



(**a**) (**b**)

Figure 3. Distribution of studies by (**a**) type and (**b**) database.

We then conducted an analysis on the keywords of each article to identify those used by the article's authors and also their frequency. We organized them into one of four groups:

1. Technology: terms related to the technology that was used, such as scanning, resolution, virtual reality, visualization.
2. Clothing: terms related to the item being scanned, such as textile, fabric, costume.
3. Museum: terms related to the museum's aim in digitizing the object, such as archiving, documentation, preservation.
4. Cultural: terms related to the historical or cultural context of the scanned item, such as Alaska native or Middle Ages.

To achieve this goal, some other procedures were carried out:

- “Compound” keywords were split; for example, the keyword “Gorenjska folk costume image analysis” was divided into three: “Gorenjska” (cultural), “folk costume” (clothing), and “image analysis” (technical);
- Keywords were aggregated by their similarity under a common simplified keyword when we found it pertinent. This happened with the keyword “National Museum of Slovenia”, which was simplified to the more general (and widely used) keyword “museums”.

Table 5 shows the keywords used, organized by type, and their frequency. The frequency of keywords is uniform—in average each keyword occurs once. The biggest group of keywords is technology-related (29 keywords), and the smallest one is culture-related (five keywords). Remaining groups are comparable in number, being 11 in the case of clothing, and 14 in the case of museum.

Table 5. Keywords by type and their frequency.

Keyword Group	Keywords
Technology	3D graphics (1); 3D imaging (1); 3D modeling (2); 3D printing (1); 3D scanning (3); 3D technology (1); 3D visualization (1); alpha map (1); augmented reality (1); digital (1); digital fashion (1); digital repatriation (1); efficient visualization (1); illustration (1); image analysis (1); image-based modeling (1); interaction design (1); interactive visualization (1); mixed reality (2); online participation (1); pattern design (1); prototype (1); storytelling (1); super high resolution (1); technology (1); thickness mapping (1); user engagement (1); user experience (1); virtual reality (2)
Clothing	accessories (1); armor (1); breastplate (1); folk costume (2); fragment (1); handicraft (1); puppetry (1); spiral staircase (1); textile (1); timber roof truss (1); woven fabric porosity (1)
Museum	archive (1); communication (1); conservation (1); cultural heritage (1); documentation (1); fashion curation (1); fashion film (1); historic preservation (1); historical fashion (1); historical furniture (1); innovation (1); museums (2); preservation (1); restoration (1)
Cultural	Alaska native (1); Early Modern period (1); Gorenjska (1); indigenous peoples (1); Middle Ages (1)

3.2. Answer to Research Objective 2

To answer Research Objective 2 (RO2: Identify the purpose driving the creation of 3D scans and the technology used) we conducted a qualitative analysis on the selected studies, extracting information about scanning devices, the type of technology used for 3D scanning, the purpose of the scan and the objects being scanned.

We classified the technology used into the following categories: structured light scanning, laser scanning, photogrammetry and computerized tomography scanning. We classified the purpose of scanning into six categories: dissemination, archiving (which might also be perceived as a form of documentation), reconstruction, technology presentation, research, and developing a digitization workflow. One study could be assigned up to two purposes in this categorization system, selecting the most important two where several were applicable. In some cases, we were not able to establish specific details; such instances are recorded as “not established” in Table 6.

The results of the qualitative analysis are shown according to the distribution of 3D technology type (Figure 4), the distribution of purposes for scanning (Figure 5) and the distribution of scanned object types (Figure 6). The most frequent technology choices were photogrammetry (six studies) and laser scanning (four studies). Other identified technologies occurred only once. The dominant purpose of 3D scanning was dissemination (eight studies) and archiving (four studies). In two studies, scans were made as a base for research. A majority (seven studies) concerned the scanning of full-size clothes; however, three studies focused on the scanning of historical clothed toys. The remaining publications concerned fragments of clothes (two studies) and armor (one study).

Table 6. Summary of technology and purpose of 3D scanning.

ID	Devices	Technology Type	Purpose	What was Scanned?
AC18	digital camera	photogrammetry	dissemination	personal objects (including clothes) brought by visitors of a museum
IE20	FaroArm	laser scanning	archiving, dissemination	puppets in clothes
IE01	TelePhotogenics Inc. Zoomage360	laser scanning	technology presentation	a doll in clothes
SC14	Nikon Metrology XTH 225 micro-CT scanner	computerized tomography scanning	archiving, reconstruction	a decorative collar
SP18 *	not established	not established	dissemination	a folk costume
GS13	device running Autodesk "123D Catch" app	photogrammetry	dissemination	historic garments
GS18	not established	photogrammetry	research, dissemination	ethnographic collections
GS17	Konica Minolta Vivid 910	laser scanning	archiving, dissemination	a waist coat
GS19a	device running Eyeexpo app	photogrammetry	dissemination	clothes collections
GS19b	not established	laser scanner and photogrammetry	research	armor, including a textile example
GS12	Breuckmann Smart Scan-HE	structured light scanning	developing digitization workflow	a small doll in clothes
GS16	Canon 5D MkIII and PhotoScan app	photogrammetry	archiving, dissemination	a folk costume

* 3D meshes were designed from scratch through Blender. Photographs and 3D scans were used to capture realistic and accurate images of the materials.

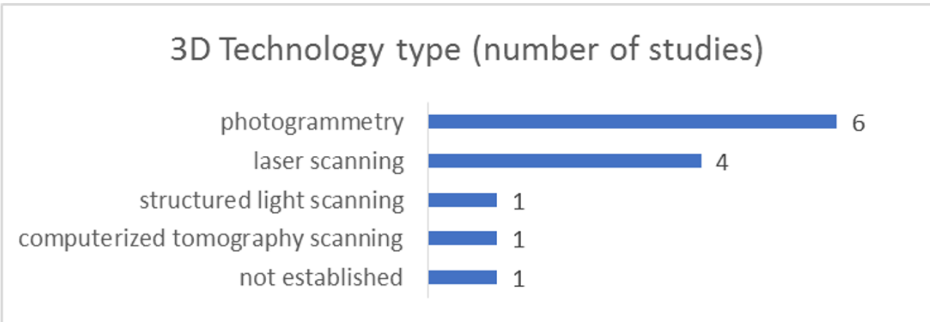


Figure 4. Distribution of 3D-technology types.

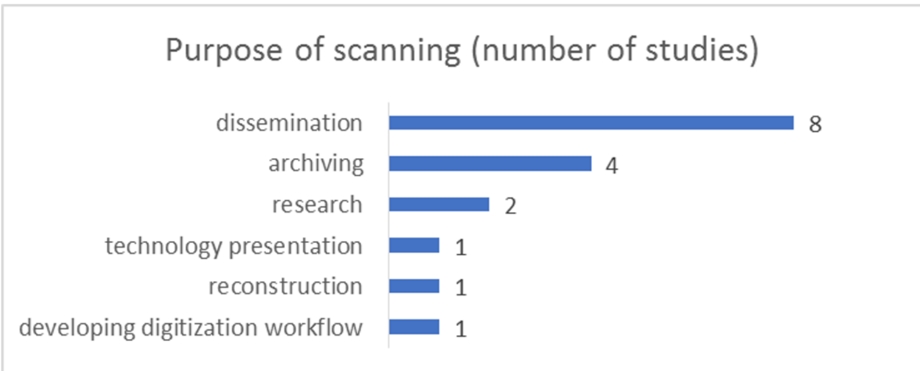


Figure 5. Distribution of reasons for scanning.

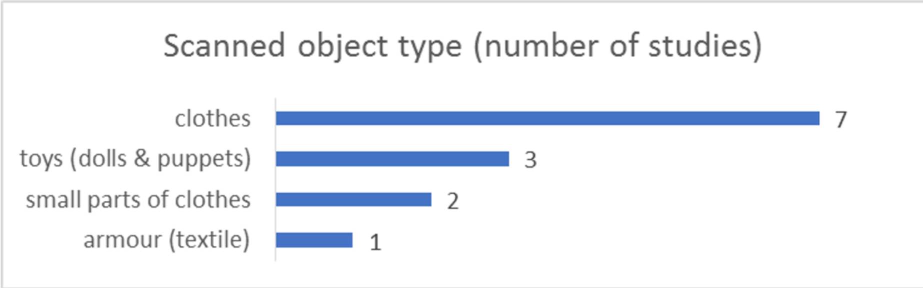


Figure 6. Distribution of a scanned object type.

3.3. Answer to Research Objective 3

To answer Research Objective 3 (RO3: Assess how well the literature describes the 3D scanning procedure), we conducted quantitative analysis on the selected papers. The five-point Likert scale was used to assess the general quality of the paper, as well as the quality of description of the hardware and software used for 3D scanning, the procedure of 3D scanning, and the background of the 3D-scanned objects. A Yes/No scale was used to determine whether the study was focused on providing guidelines. See Table 7 for details.

Table 7. Quality evaluation of identified studies.

ID	Hardware and Software	Procedure	Objects	Guidelines	General Quality
AC18	3	2	1	No	2
IE20	4	3	4	No	2
IE01	4	3	2	No	1
SC14	5	4	4	No	5
SP18	3	4	5	No	4
GS13	3	3	2	Yes	4
GS18	2	2	3	Yes	4
GS17	4	3	2	No	3
GS19a	2	1	2	No	2
GS19b	1	1	4	No	1
GS12	4	5	2	Yes	3
GS16	4	4	4	Yes	4
Average	**3**	**3**	**3**		**3**

The data seem to show a high degree of variation in the quality of the studies. Figure 7 shows the distribution graphs of the quality by each one of the three dimensions—hardware and software, procedure, and objects. The charts imply the following conclusions:

1. Hardware and software is the dimension the studies' authors describe with the greatest level of detail across the board, leading to a higher "quality" score: 50% of the studies received a score of 4 (good) or 5 (very good), while 75% of the studies were at least moderate (3).
2. The level of detail provided on procedure was also relatively good: at least 66% of the studies scored 3 (moderate) or above.
3. There appears to be greater heterogeneity in the quality of descriptions of objects: 50% of the studies were found to present a poor or very poor description of the objects.

An aggregation of the three dimensions of quality is presented in Figure 8. It illustrates that there is a great heterogeneity between the studies, having an almost uniform distribution between the five categories of quality (from very poor to very good).

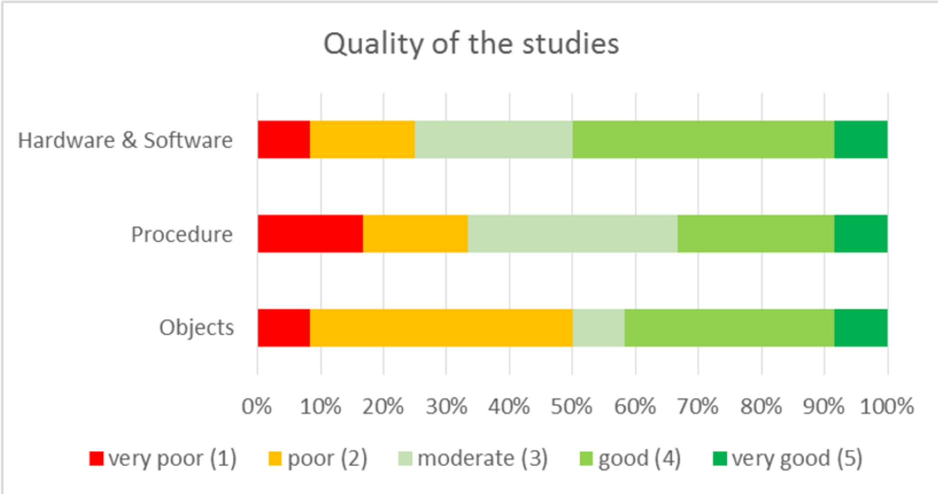


Figure 7. The quality of the selected studies.

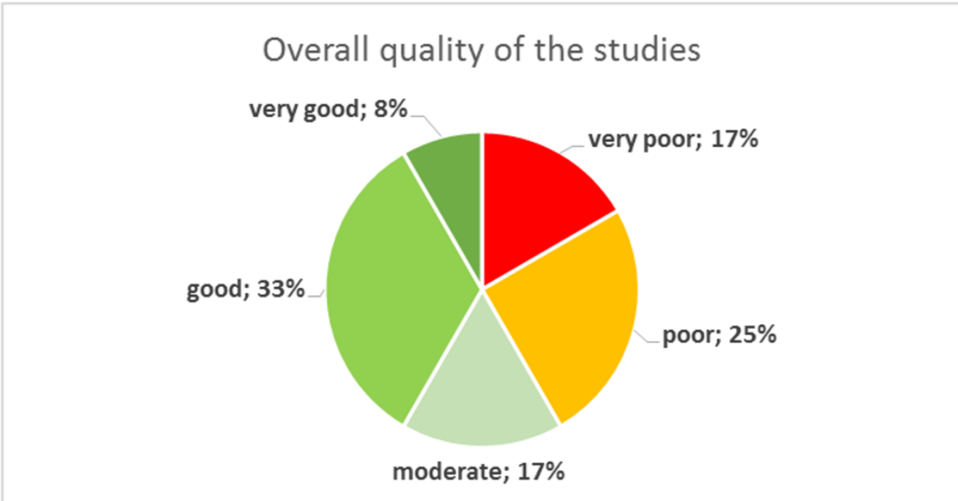


Figure 8. Overall quality of the selected studies.

4. Conclusions

This article discovers and compares methodologies of 3D scanning of historical clothes presented in the literature, in order to determine if a new methodology is needed. In order to answer the research question, How have 3D scanners been used to digitize historical clothes? we established three research objectives:

RO1: Identify whether studies on this topic exist and how many there are.

RO2: Identify the purpose driving the creation of 3D scans and the technology used.

RO3: Assess how well the literature describes the 3D scanning procedure.

In terms of RO1, after screening, we identified 12 publications on this topic, a mix of journal articles and conference proceedings. The first one dated from 2001, and the remaining 11 were all published between 2012 and 2020.

We can only speculate on the reasons why there are so few studies on the 3D scanning of historical clothes. One hypothesis, as stated in Section 1.1, is that the application of 3D scanning technology in the digitization of cultural heritage objects is still a relatively young field and knowledge about these techniques is not widespread. A second hypothesis is that authors simply do not feel it is relevant to publish on this specific type of object (historical clothes), perhaps considering the challenges of scanning these artefacts (such as the problem of shinny surfaces) to be the same as for other objects—in other words, that there is nothing new to be "discovered" or published. We would argue that this is not the case, as historical clothes have particular characteristics (e.g., size, texture, and shapable volume) that present specific challenges when it comes to scanning. Last, there is the hypothesis that museums still do not see 3D models as "relevant" for certain purposes. As the literature suggests, 2D photographs, 360º photographic views, 3D CAD models and photogrammetry-based 3D models are often preferred for purposes of dissemination.

Regarding RO2, to discover the reasons for 3D scanning, we found that a substantial majority of 3D-scanning projects were carried out for dissemination purposes (eight instances), followed by motivations linked to archiving (four) and research (two). This finding is unsurprising given the rising importance of digital images for facilitating public access to museum collections, whether online (for example, enabling people to explore collections without visiting the museum) or to be deployed in interactive digital media as part of an in-house exhibition.

In terms of the technologies used (also covered in RO2), it turned out that 40% of the articles were not, in fact, about true 3D scanning; in fact, they were on photogrammetry, which, according to the scientific literature, is a separate technology. We included them to highlight a degree of confusion among authors as to what does and does not constitute 3D scanning. After photogrammetry, the most common approach was laser scanning, which was discussed in four of the articles. The surprising finding here was the general under-utilization of structured light scanning, which in our opinion is potentially better-suited technology for 3D scanning of historical clothes, at least in comparison to the other scanning technologies identified.

Turning to RO3, we found very wide variability in the quality of articles, with 41% classed as good or very good, but 42% described as poor or very poor. Generally speaking, the articles tended to deal with technical issues, such as the hardware and software, quite thoroughly, followed by procedure. Fewer articles gave a thorough description of the objects themselves. However, ultimately, the question of whether the focus is on the technology, the procedure, or the object will depend on the specific topic of a given article and the aims of the research it describes.

Generally speaking, we found there was a lack of high-quality articles dealing with the 3D scanning of clothing, despite the fact that this technology is potentially suited to the digital preservation of these complicated amorphous objects. We also found that only a third of the articles offered guidelines about the process. This suggests there may be scope—or even a need—for further studies exploring the relevant techniques in more detail, thus helping to build a body of best practice among museum professionals and digitization specialists.

With this article, we aimed to systematize the state-of-the-art on this topic and; as we have seen, the field at this point remains a very small and fragmented one. We found that most of the identified studies failed to provide a fair and complete description of the methodology used. We believe that authors should thoroughly document all technical aspects of their 3D scanning process, including the hardware and software used, the procedures undertaken, and the conditions in which the scanning was performed (such as the room, the light setup, and so on). A detailed explanation of the scanned artefact should also be provided, covering its size and shape but also every aspect of the fabric that was taken into consideration (such as textures and colors). It is also important to explain the purpose of the digitization project (for example, dissemination or preservation), as we believe this greatly influences the procedure (for example, detail is more important for preservation than for dissemination).

Three-dimensional scanning technology has already proven to be of tremendous value for museums in their mission to preserve, study, and disseminate history and culture. The topic of the 3D scanning of historical clothes is clearly under-explored, especially in the perspective of UN and EU initiatives and funding. Our analysis revealed that a complex and coherent methodology proposal that could address these needs is missing, and this was a tremendous motivational trigger—as a result, such methodology was proposed in another article [33]. We hope that this article offers a small but important contribution to bringing this topic to light and allotting it the importance it deserves.

Author Contributions: Conceptualization, K.Ż., F.S., J.K.; methodology, F.S. and K.Ż.; software, K.Ż.; validation, G.H.; formal analysis, F.S. and K.Ż.; investigation, K.Ż., J.K. and F.S.; resources, J.K., K.Ż., G.H. and F.S.; data curation, K.Ż., J.K. and F.S.; writing—original draft preparation, F.S. and K.Ż.; writing—review and editing, K.Ż., F.S., G.H., J.K.; visualization, F.S.; supervision, K.Ż.; project administration, K.Ż.; funding acquisition, J.K. and K.Ż. All authors have read and agreed to the published version of the manuscript.

Funding: This article was financed by the Lublin University of Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank the Centre for Studies in Education and Innovation (CI&DEI) and the Polytechnic of Leiria for their support.

Conflicts of Interest: The authors declare no conflict of interest.

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