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Digital restoration and reconstruction of heritage clothing: a review

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Abstract

Historical, folk, and opera costumes are part of cultural heritage, embodying the history, culture, art, and spirit of given nations. Due to aging and various damages, handed-down and unearthed historical clothing is often fragile and complex to preserve. Recently, digital methods have emerged as a meaningful way to restore and reconstruct all kinds of heritage clothing. The appearance of heritage costumes can be preserved permanently and presented to the public in a more accessible and interesting way via digitization. However, there is a lack of systematic review on this topic. To fill this gap, recent progress in digital restoration and 3D virtual reconstruction of heritage clothing is reviewed in this article. On the one hand, the methods and advantages of digitally restoring damaged archaeological costumes and fabrics, as well as damaged clothing images in archaeological murals, are summarized and emphasized. On the other hand, the digital reconstruction and virtual simulation of heritage costumes from different prototypes with known or unknown original appearances using different digital frameworks are presented and discussed. Furthermore, general steps and challenges in the digital reconstruction process, as well as future directions for digitalizing heritage clothing, are also discussed.

Keywords Heritage clothing, Historical costumes, Opera costumes, Digital restoration, Digital reconstruction, Virtual display

Introduction

Heritage can be defined as something that is or may be inherited by individuals or communities and passed on to successors [1]. According to Vecco [2], one of the first texts that defines the concept of heritage is the International Charter of Venice (1964), in which heritage is described as living witnesses to age-old traditions. Early protection methods for cultural heritage focused on its materiality and largely depended on the judgment of professional experts. Over time, the new interpretation of heritage emphasizes the social and cultural meanings behind these objects and focuses more on preserving the cultural knowledge related to creation [3]. With the launch of the Convention for the Safeguarding of the Intangible Cultural Heritage (2003), intangible heritage is explained as an aggregation of knowledge systems, rituals, arts and crafts, and social practices, along with tangible items like objects, instruments, and living spaces, which are linked to their accomplishment. Heritage clothing, as a nation's tangible cultural heritage (TCH), reflects its past living customs and culture. At the same time, the spinning, dyeing, weaving, and embroidering skills of traditional clothing are precious intangible cultural heritage (ICH) that condenses the wisdom and ingenuity of human creation. However, the unearthed historical costumes have been eroded for a long time, leading to various degrees of damage. It is often difficult to restore the original appearance of historical clothes, and direct repair means may cause secondary damage. Meanwhile, historical clothing relics are constantly aging. Physical protection methods can only slow down the

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aging process, which cannot preserve clothing relics permanently. Therefore, restoring and preserving heritage clothing is a highly urgent task.

Unlike traditional restoration methods, digital means can provide a new path for restoring and inheriting heritage costumes. For one thing, virtual restoration by digital means can greatly avoid direct contact with historical clothing relics and reduce the risks of secondary damage. For another, digital means provide easy access to not only the effective preservation but also the online display and sharing of heritage costumes, which can enable more people to understand traditional costumes and promote their contemporary dissemination. For these advantages, digital means have attracted much attention from scholars in recent years. More specifically, the keywords "historical clothing or costume or dress" and "conservation or restoration or reconstruction" were used to search for related research topics on heritage clothing in the Web of Science Core Collection database. After screening, there are 112 related research papers. The visualization software VOSviewer was used to analyze the co-occurrence of keywords in these papers, and the corresponding output is shown in Fig. 1. It can be seen that the related research involves many fields, such as clothing, cultural heritage, archaeology, computer science, human engineering, chemistry, etc. It is worth noting that in recent years, three-dimensional (3D) reconstruction of historical clothing, 3D modeling, virtual simulation, and reverse engineering have become important research hotspots in the fields of clothing and archaeology, demonstrating the feasibility of restoring and inheriting heritage costumes by digital means. In the process of digital restoration and reconstruction of heritage clothing, computer graphics software is needed to generate 3D clothing from two-dimensional (2D) clothing images and prototypes. With the development of computer technology, 3D digital technologies, including 3D scanning, 3D modeling, virtual reality (VR), augmented reality (AR), etc., have been applied to related research in the fields of cultural heritage [4].

Currently, there are some relevant articles that introduced recent projects and works about realizing the digitization of heritage costumes. Kang [5] discussed several projects about clothing digitization, including Turandot, Empress's New Clothes, Fashion Curation '13, Rococo Costumes, and Drexel Historic Costume Collection, so as to emphasize the exhibitory and educational uses of virtual costumes. Dvořák et al. [6] briefly reviewed the common methods of generating 3D virtual historical clothing before conducting the presentation of historical clothing digital replicas in motion. Focused on 3D scanning methods, Żyła et al. [7] reviewed and compared different

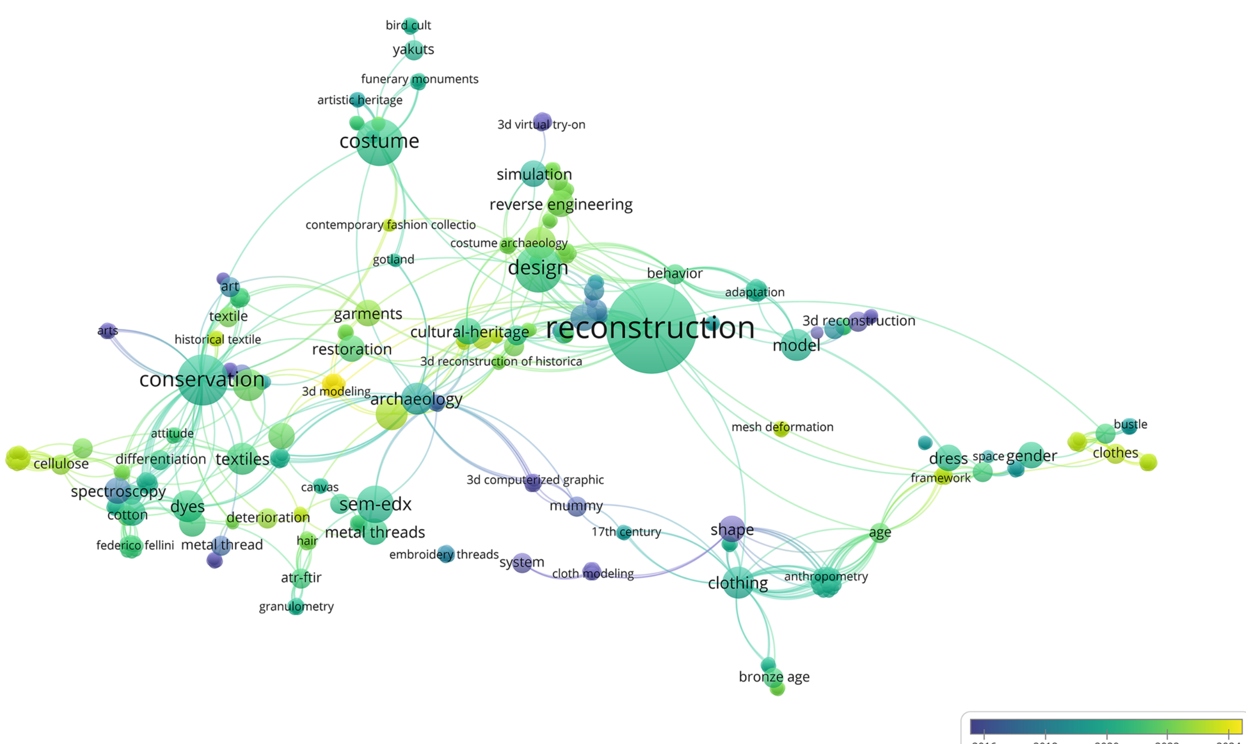

Fig. 1 Keywords co-occurrence network of "historical clothing or costume or dress" and "conservation or restoration or reconstruction" via VOSviewer

scanning methodologies to obtain digital replicas of historical clothes. In the Introduction Section of Kuzmichev et al.'s article [8], several references regarding the virtual reconstruction of historical costumes were mentioned and general steps for digital reconstruction were summarized. However, most of the previous relevant studies were either concentrated on reviewing some specific digital methods or presented a brief introduction to the development of this field. A systematic review of the detailed procedures and challenges of digitally restoring and reconstructing heritage clothing is relatively lacking. In this context, this review will be very timely and important.

This review intends to fill this gap by providing a comprehensive summary concentrating on the digital restoration and reconstruction of heritage clothing. The paper includes the following four main parts. First, the digital methods commonly used to realize the digitalization of garments are classified and introduced in section "Methods for digitizing heritage clothing". Next, research progress on the digital restoration of damaged clothing-related archaeological heritage is discussed in section "Digital restoration of damaged clothing-related archaeological relics". Then, the 3D virtual reconstruction of heritage costumes with known or unknown original appearances is reviewed separately in section "3D virtual reconstruction of heritage clothing". Finally, the general steps, challenges, and future development directions of digitizing heritage clothing are analyzed and discussed in section "Discussion and future directions".

Methods for digitizing heritage clothing

As mentioned in section "Introduction", this review focuses on the application of digital technologies in restoring and reconstructing heritage costumes. Figure 2 shows the common approaches to digital restoration and reconstruction of heritage clothing.

The digital restoration mainly involves image inpainting of photographs of damaged clothing-related cultural heritage. As shown in Fig. 2, image inpainting methods

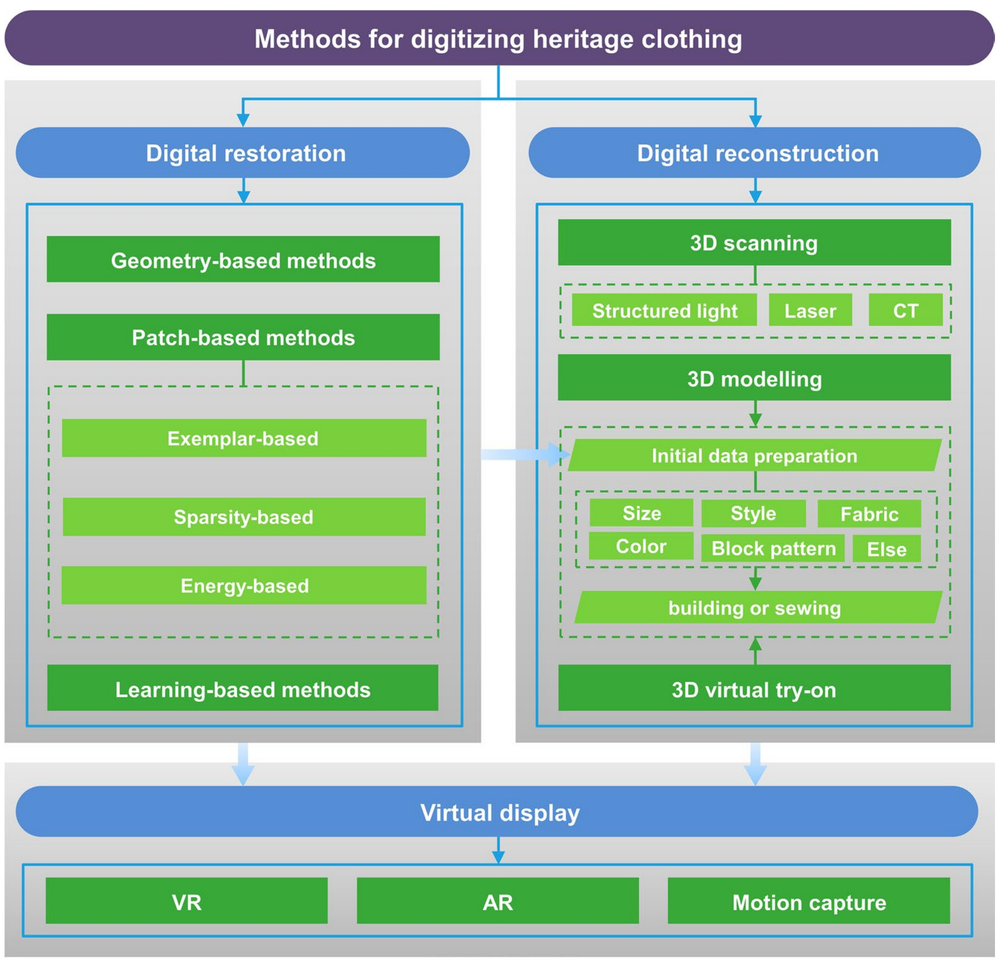

Fig. 2 Approaches to digital restoration and reconstruction of heritage clothing

usually include geometry-based methods, patch-based methods, and learning-based methods [9]. Geometry-based methods introduce smoothness priors and diffuse the texture or structure information from the known region into the missing region. This kind of method can obtain excellent visual effects when restoring straight lines, curves, or relatively small missing areas, but it is not good at restoring texture information or large missing areas [10]. Patch-based methods come from texture synthesis, which makes full use of self-similarity priors and statistical patterns. Commonly used patch-based methods include exemplar-based, sparsity-based, and energy-based methods [9]. It should be noted that the Criminisi algorithm, as one of the exemplar-based methods, has been widely used as a baseline for comparison [9]. Different from geometry-based inpainting algorithms, patch-based methods can produce excellent visual effects when restoring large missing areas. However, if the relevant information about the structure or textures cannot be found in the source area of the image itself, this method will produce blurry or unnatural results, especially for texture areas [10]. Deep learning methods such as the convolutional neural network (CNN) and generative adversarial network (GAN) have been introduced into the field of image inpainting [11]. The basic idea of inpainting images with deep learning methods is to learn the semantic information of images accurately at first and subsequently predict the missing areas of images based on the learned information [12]. One great advantage of deep learning methods is that the restoration results are usually more logical [12]. However, it should be noted that these types of repair methods require massive amounts of data and a lot of time to train the network. The inpainting tasks can be very challenging if the structure information is missing in the damaged area, especially when there are not enough paintings of the same style to support a learning system to infer the structures [10]. Generally, the above image restoration methods are becoming increasingly widespread as a useful tool in various cases of restoring damaged clothing-related cultural heritage.

The digital reconstruction aims at generating 3D virtual replicas of garments. Currently, there are a variety of technologies that are commonly used to obtain 3D digital models of cultural heritage, such as CAD modeling, 3D scanning, image-based photogrammetry, 360 panoramas, modeling with range imaging cameras, and so on. Since this review is focused on heritage costumes, attention will be paid mainly to the following three ways, i.e., 3D scanning, 3D modeling, and 3D virtual try-on, as shown in Fig. 2. 3D scanning technologies, including computed tomography (CT), laser scanning, structured-light 3D scanning, etc., are potential methods to acquire 3D models of real historical clothing objects in situ. CT, as a non-destructive analysis method, is able to detect the 3D internal structures of an object [13]. Laser scanning directs the laser beam to a specific point in space and calculates the distance according to the returning beam [7]. To the best of our knowledge, the application of CT and laser scanning to generate digital replicas of historical clothing is relatively limited. Structured-light scanning works by projecting an image onto the scanned object and calculating the 3D topography of the object's surface based on the differences between the original and the projected image. This technology is able to scan objects from a few millimeters to several meters with a high spatial resolution of less than a millimeter [7], making it applicable to the reconstruction of costumes. 3D modeling methods are usually implemented by the parameterization of clothing at first and a subsequent generation of 3D digital replicas using these parameters. 3D virtual try-on can be done by sewing pattern blocks to obtain the 3D model of costumes with the aid of contemporary software like CLO3D [14, 15]. Both 3D modeling and 3D virtual try-on include initial data preparation and 3D model generation by building or sewing, which will be explained in detail in section "Discussion and future directions".

With the aid of digital approaches such as VR, AR, and motion capture, digitally restored or reconstructed heritage costumes can be displayed and disseminated more conveniently. VR is a kind of digital technology that involves the creation and visualization of an imaginary environment and makes the users feel like they are in that environment [16]. AR is considered as one of the most advanced ways to connect a person with a computer by combining real and virtual objects with a 3D registry. This technology allows for real-time interaction between the user and the imaginary environment [16, 17]. VR enables the display of digitalized costumes in an imaginary environment, such as a VR museum, while AR provides the users with a playful experience to interact with heritage clothes, which is valuable and rarely seen in daily life. Motion capture refers to the application of digital methods for tracking and recording the movements of objects or living beings in space [18]. This technology makes it possible to capture the movement of garments worn on the human body. Since virtual display approaches are not the focus of this article, relevant applications of VR, AR, and motion capture in presenting costumes will only be briefly introduced in section "The application of digital methods in displaying restored and reconstructed heritage costumes".

Digital restoration of damaged clothing-related archaeological relics

Archaeological textiles are highly vulnerable objects and often in a fragmented state when they are excavated [19]. The traditional methods for restoration and protection seem to be not only time-consuming but also unrepeatable owing to the strong dependence on operators' skills and aesthetics [20]. In contrast, the physical contact of archaeological textiles with humans can be greatly reduced by digital restoration approaches, which favor preserving historical textiles. For these reasons, digital techniques have gradually replaced traditional ones, introducing revolutionary methods for the protection of cultural heritage.

Damaged archaeological costumes and fabrics

Based on image inpainting methods, the patterns of archaeological costumes and fabrics can be restored in the form of digital images. The structure and geometric layout of damaged parts are critical problems in the digital repair process. Sun et al. [21] proposed a structure-guided virtual restoration method to improve the inpainting quality of silk cultural relic images. The structure lines in damaged regions were repaired by an adaptive curve fitting algorithm at first and then modeled as boundary functions to improve the filling priority of sample blocks in the vicinity of these structure lines. In this way, image structure confusion is greatly avoided, and the credibility of the repair information is also increased, achieving good restoration results with few blurry or unnatural regions for several damaged ancient silk relics [21]. Tang et al. [22] improved the classical Criminisi algorithm by introducing the structure tensor term, which shows a more satisfactory restoration in two tested cases, i.e., an image of damaged fabrics and an image of complete fabrics with man-made damage.

Besides, the development of deep learning techniques provides effective methods for image remediation topics, including damage remediation of heritage. For instance, Sha et al. [23] constructed an improved GAN image restoration model to restore ancient textile images. The YOLOv4-ViT network was adopted to classify the pattern elements of 2057 ancient textile images from the Mashan Tomb, and these classified textile images were used to train the GAN model [23]. In this way, the incomplete structure and patterns of ancient textile images can be restored, as shown in Fig. 3. Also, Chen et al. [24] built a logical complementary model of garment heritage pattern defacement layout based on GAN to assist in restoring the broken patterns on silk clothing. In addition, Stoean et al. [25] carried out semantic inpainting of traditional Romanian vests using perceptual loss within the GAN-based approach. Clearly, the above relevant studies indicate that digital methods open a whole new way for the restoration of damaged archaeological clothing and fabrics.

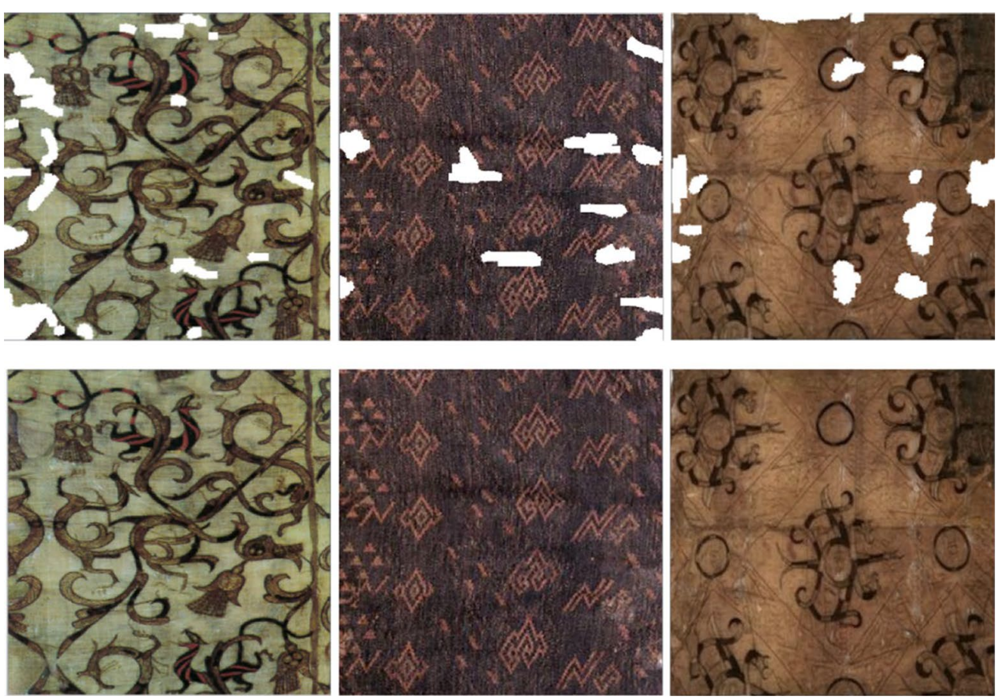

Fig. 3 Comparison of ancient textile images before and after the restoration. Reproduced from reference [23] with the permission of the authors

Damaged clothing images in archaeological murals

Ancient murals are important objects of the human cultural heritage, in which a large number of ancient figures' dress images are recorded. Due to the degradation caused by long-term environmental exposure and human activities, many ancient murals are suffering from serious diseases such as scratches, cracks, corrosion, and paint loss [26]. In recent years, traditional and deep-learning-based image inpainting methods have been used to fill the missing or degraded areas of damaged ancient murals.

The traditional geometry-based and patch-based inpainting methods are widely used to repair damaged clothing images in archaeological murals. Based on geometry-based methods, Jaidilert et al. [27] repaired Thai murals in the Rattanakosin period (Rama I and Rama II). Cao et al. [28] developed an adaptive sample block and local search algorithm on the basis of the Criminisi algorithm to conduct the restoration of damaged areas in Kaihua Temple murals from the Song Dynasty. Wang et al. [9] adopted a patch-based method to repair the damaged murals of Mogao Grottoes under the guidance of structural line drawings. The line drawings created by the Dunhuang Research Academy were utilized to complete the missing structural information in the damaged areas. The above human-labeled structural information was further adopted to modify the patch structure complexity (PSC) of structure patches, yielding restored images with better quality [9]. Similarly, based on the patch-based method, Wang et al. [10] repaired the figures of dressed people in the damaged Dunhuang murals, in which the weighting methods of global feature patch and local feature patch are designed to improve the visual appearance of damaged mural figures and costumes.

In addition, deep-learning-based inpainting methods are also frequently applied in restoring images of damaged clothing in murals. Deng et al. [29]. developed a structure-guided two-branch model on the basis of the GAN model to virtually restore the damaged murals in two stages: the structure reconstruction stage employing fast Fourier convolution and gated convolution to reconstruct the missing structures, and the content restoration stage restoring the missing content of murals with the guidance of reconstructed structures. Wang et al. [30] proposed a Thanka mural inpainting method on the basis of multi-scale adaptive partial convolution and stroke-like masks, which enables the restoration of multiple irregularly damaged areas without any post-processing. Based on the GAN model, Lv et al. [31] constructed a two-generators-connected mural image restoration network, showing outstanding inpainting performance in the restoration of Dunhuang murals. Cao et al. [32] complemented mural images with complex textures and large missing areas using a consistency-enhanced GAN model. Ciortan et al. [33] developed an inpainting algorithm with an edge generator and a color generator based on the GAN model to achieve a visually satisfactory restoration of digital images of the Dunhuang murals. Li et al. [34] proposed a line-drawing-guided progressive inpainting strategy to separate the inpainting of mural images into structure restoration (by line drawings) and color correction (by local color adjustment), which was implemented by a patch-based GAN with 2 generators (a structure generator and a color generator) connected to the same discriminator. Figure 4 shows the comparison between the inpainting with and without the assistance of line drawings, indicating that Li et al.'s strategy is effective in alleviating the commonly existing color bias problem and improving the restoration result with fewer blurry regions (see the comparison between Fig. 4d and e). In short, with the aid of deep learning methods, the damaged clothing image in murals with large missing areas can be repaired with satisfactory visual effects. The restored mural images can not only provide another source to investigate and explore the past living customs and culture of the nation, but also be taken as the prototype for the 3D digital reconstruction of historical clothing recorded by archaeological murals.

3D virtual reconstruction of heritage clothing

With the rapid development of digital technology, the digital reconstruction of heritage clothing has become more and more convenient. There are many software packages that can provide efficient and convenient technical support for 2D pattern block drawing (e.g., Fuyi CAD, AutoCAD, T-FLEX CAD, and Modaris [35, 36]), 3D modeling (e.g., 3dsMax, Blender, Maya, and Cinema4D [36, 37]), and 3D virtual try-on (e.g., CLO3D, DC Suit, Marvelous Designer, and Optitex [36, 38]) of clothing. The application of one or more of the above software packages enables the realization of various functions such as pattern block making, fabric simulation, decorative pattern design, 3D model generation, dynamic virtual display, and so on.

Clothing reconstruction is a complicated work that must be based on multi-faceted research, including structural analysis, knowledge of old technologies, and, if possible, the iconography of a given historical period and analogous objects that have survived [39]. Table 1 summarizes several works of reconstruction based on unearthed or handed-down clothing objects (3D), ancient paintings (2D), and historical images of clothing illustrations or pattern blocks (2D). There are two main cases of clothing reconstruction. The first is to replicate an object that already exists [40], i.e., one with a known original appearance. This case of digital reconstruction is relatively simple owing to the access

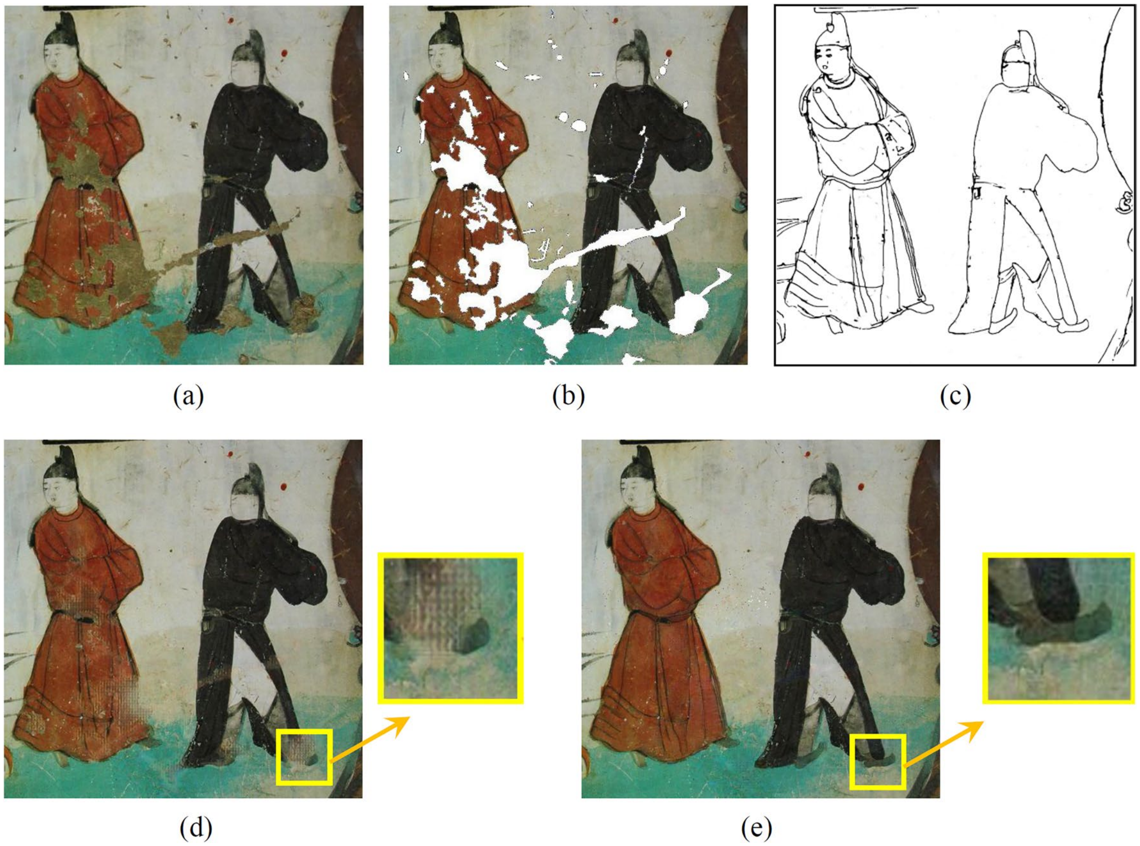

Fig. 4 Digital restoration of one mural image with and without the assistance of line drawings. **a** The damaged mural image; **b** the mask for damaged region; **c** the line drawings of mural image; **d** the restored mural image without line drawings; **e** the restored mural image with line drawings. Reproduced from reference [34] with the permission of the authors

Table 1 Reconstruction techniques for different types of heritage clothing

Main sources of reconstructed objects	Reconstruction types	Reconstruction techniques	References
Unearthed or handed-down clothing objects	Real costume digitization (nearly complete)	2D block pattern drawing, 3D virtual try-on	[35, 41–43]
		Structured-light 3D scanning	[44]
	Real costume digitization (part damaged)	2D block pattern drawing, 2D fabric, pattern and color restoration, 3D virtual try-on	[15, 24, 45, 46]
		3D modeling, 3D virtual try-on	[37, 47]
Costumes in ancient paintings	From 2D to 3D	2D block pattern drawing, 2D fabric, pattern and color restoration, 3D virtual try-on	[15, 38, 48–50]
Historical clothing block patterns	From 2D to 3D	2D block pattern drawing and parameterization, 3D virtual try-on	[51–53]
Historical clothing illustrations	From 2D to 3D	2D block pattern drawing and parameterization, 3D virtual try-on	[8, 36, 54]

to a lot of details about the structure, color, and fabric of the clothing. The second involves remaking an object that doesn't actually exist (i.e., with an unknown original appearance): whether a garment in a painting, a clothing pattern, or a garment described in historical texts. The absence of clothing details poses a big challenge to researchers, making the digital reconstruction process more complicated and time-consuming. In this section, recent progress in the digital reconstruction of these two categories of heritage costumes will be introduced.

Real heritage clothing objects with known original appearances

Heritage clothing, including historical clothing, folk clothing, opera clothing, etc., is an important carrier of culture, containing rich information about the art, spirit, history, society, and life of different countries from different periods. With the continuous advancement of archaeological excavations, many historical costumes reappear in the world, enabling contemporary people to understand the original appearance of costumes in different periods. At the same time, some traditional costumes and opera costumes have been properly kept by family members and collectors, and thus preserved to this day. However, these clothing objects are usually presented to the public either with the protection of windows or in the form of 2D images, which limits the dissemination of heritage costumes. Thus, it is a meaningful task to complete the 3D reconstruction and dissemination of heritage clothes with known original appearances by digital methods.

For example, Chinese traditional operas such as Kunqu opera, Cantonese opera, and Peking opera, which can still be seen on the opera stage today, are listed as United Nations Educational, Scientific and Cultural Organization (UNESCO) representative works of human ICH. In addition, Yue opera, Henan opera, Shaanxi opera, etc. are included in China's national intangible cultural heritage list. As an indispensable part of opera performances, Chinese opera costumes belong to precious cultural heritage. Liu et al. [41] built the 3D digital models of 12 sets of traditional Yue opera costumes following the steps below: First, analyze the style, structure, fabric, color, and decorative pattern; Second, draw the 2D pattern blocks with CAD tools; Third, import the 2D pattern blocks into 3D virtual try-on software and virtually sew the clothing pieces from inside to outside; Fourth, set the color, fabric, and decorative pattern to complete the 3D reconstruction. Following similar steps, 12 sets of traditional Qin opera costumes were transformed from 2D images into 3D virtual replicas by Liu et al. [35]. Figure 5 shows the digital reconstruction displays of Qin opera costumes [35], indicating a good visual consistency between the prototype and the digital replica can be achieved by digital methods. In addition, through the digital reconstruction of opera costumes, these two works [35, 41] extracted the representative cultural symbols of Yue opera and Qin opera costumes. On this basis, innovative designs of a series of opera costumes were carried out, which further promoted the contemporary protection and inheritance of opera costumes.

Similar to opera costumes, folk costumes are another type of heritage clothing with known original appearances. Kočevar et al. [42] modeled a woman's folk costume from the Gorenjska region in Blender software. All the parts of this folk costume were modeled in a sequence of underskirt, upper skirt, rokavci shirt, bra, zavijačka head piece, belt with a bow, high socks, and shoes, and meanwhile the fabric properties were selected. Finally, the colors and repeat patterns of each part were edited. Yu et al. [43] proposed a fast-scanning method together with enhanced generation algorithm of 3D point cloud to digitally reconstruct the physical shape of traditional folk clothing.

The development of structured-light 3D scanning technology provides another potential method to reconstruct historical costumes. Sufficient completeness of historical clothing is a prerequisite for the 3D reconstruction of historical clothing by structured-light 3D scanning. In other words, the historical clothing should be in its original appearance as much as possible. Montusiewicz et al. [44] applied structured-light 3D scanning technology to digitally reconstruct the Emir of Bukhara's costume (Uzbekistan) from the end of the nineteenth century, consisting of the gown, turban, and shoes. The structured-light 3D scanning methodology mainly contains 5 steps. In step 1, a detailed plan is made, including the selection of clothing objects to be scanned, the arrangement of objects during scanning, and the required lighting. In step 2, the scanning process is implemented properly. In step 3, the scanning result of each clothing object is preliminary processed at the scanning location and time to examine the quality of scanning and decide whether a repeated scanning process is needed. In step 4, the scanning results are fully processed to obtain the 3D base model for the scanned clothing objects. In step 5, the base model is transformed into a dissemination model based on specific requirements for dissemination [44]. In this way, the virtual reconstruction dovetails nicely with the real objects selected for 3D scanning. Therefore, structured-light 3D scanning is an efficient way to acquire in situ 3D digital data of historical clothing.

In addition to the above-mentioned set of historical costumes that are relatively well preserved in museums, some historical costumes have experienced a lot of damage when they were unearthed. These damaged costumes can also provide visual references to their original appearances from the undamaged parts. However, the digital reconstruction process of these garments is more complicated and usually needs to be based on a multifaceted analysis of the structure, size, fabric, color, pattern, and ancient craft of clothing making. Liu et al. [45] applied a 3D–2D–3D method to the digital reconstruction of the Plain Unlined Silk Gauze Gown unearthed from Mawangdui Han Tomb in China with the procedures below: Firstly, the contour line was extracted from the picture of damaged clothing to generate a preliminary

Fig. 5 Digital reconstruction displays of Qin opera costumes. Reproduced from reference [35] with the permission of the authors

3D model by virtual try-on in CLO3D software; Subsequently, the human–computer interaction was conducted to draw dividing lines on the 3D model, make some corrections on the 3D model such as stretching and freezing, and unfold the 3D model to obtain a corrected 2D pattern block; Finally, the 3D digital reconstruction was performed in combination with corrected 2D pattern blocks and professional analysis on the style, fabric, color, and other aspects of the clothing [45]. In Wu et al.'s work [46], the above 3D–2D–3D method was also applied to realize a successful digital reconstruction of a straight-front robe from the Mawangdui Han Dynasty tomb. It is indicated that the digital reconstruction exhibits a satisfactory performance in the reconstruction of partly destroyed historical costumes. Besides, it is worth noting that the digital reconstruction of historical clothing can be assisted by the digital restoration technology discussed in section "Digital restoration of damaged clothing-related archaeological relics", if the relevant information about decorative patterns is absent. For example, Chen et al. [24] proposed a garment heritage restoration method based on deep learning to recover the decorative patterns, which greatly support the 3D digital reconstruction of the Pale Brown Lace-encrusted Luo Unlined Coat from Huang Sheng's tomb in China. However, the method proposed in Chen et al.'s study has a relatively high requirement for the proportion of missing and damaged information on garment heritages.

Apart from visualizing and disseminating the historical clothing introduced above, the digital reconstruction can also be used to analyze specific issues related to historical clothing, acquiring new insights about the way to use and wear historical clothing in the past. For example, owing to the specific physical and mechanical properties of metallic materials, historical clothing made from metallic materials exhibits a unique draping behavior when worn on the human body, bringing new challenges to the reconstruction of historical clothing. Unlike textile materials, metallic materials are usually not deformable, making them unable to be bent, stretched, or pressed freely. To handle this problem, Wijnhoven et al. [47] developed a new method to replicate and reconstruct mail armor in virtual reality by a combination of 3D modeling of armor laid out flat under the influence of gravity and virtual try-on using rigid body simulation. The rigid body simulation constrains the horizontal and vertical distances between the connected rings of the mail armor so that the influence of gravity on the draping behavior can be coupled in the virtual try-on process. Figure 6 shows the digital replicas of mail armor generated through traditional cloth simulation (without the influence of gravity on draping behavior) and rigid body simulation (with the influence of gravity on draping behavior). As can be seen, the distances between the rings in model 1 are constant throughout the garment which doesn't match the actual mail armor worn on the human body. In contrast, the mail fabric in model 2 is stretched horizontally below the neck opening and stretched vertically in the trunk, reproducing the draping of the mail armor much more accurately. Besides, digital reconstruction exhibits great potential in investigating the behavior of historical clothing, such as stress analysis, strain analysis, air gap analysis, and so on. Moskvin et al. [37] studied the behavior of the equipment of a Germanic warrior from the second–fourth century AD, which consisted of trousers, a tunic, shoes, a mail coat, an under-armour garment, and a belt, by a combination of various digital software including CLO3D, Unreal Engine, Blender, Range, and PicPick. The stress analysis (Range software) suggests that a belt is able to make wearing this military equipment more comfortable when moving; The strain analysis (CLO3D software) indicates that this military equipment causes low levels of strain in 5 poses using different types of weapons; While the air gap analysis (Blender software) reveals that the mail coat of this military equipment can offer enough room to accommodate a thick under-garment comfortably [37]. Based on these examples, it is demonstrated that digital reconstruction can act as a powerful research tool to deepen the knowledge of historical clothing.

To summarize, the 3D reconstruction exhibits the following advantages in the research, preservation and dissemination of heritage clothing: (1) the basic appearance of historical clothing can be preserved permanently; (2) the detailed information about the style, size, structure, fabric, color, decorative pattern, ornament and collocation of heritage costumes can be stored; (3) the way to wear and collocate clothing in different historical contexts and specific use occasions can be displayed through virtual fitting; (4) the 3D reconstruction provides a 360° virtual view of heritage clothes, enabling the public to catch sight of every detail more easily and more conveniently and deepening the public's understanding of costume heritage; (5) the elements of heritage costumes can be integrated into the innovative design of modern clothing, which is beneficial for the dissemination of cultural characteristics carried by historical clothing; (6) the 3D reconstruction methods, when combined with archaeology and history, are able to enrich the knowledge about historical clothing. Thanks to these advantages, 3D digital reconstruction is becoming more and more important

Fig. 6 Digital replicas of the mail armour. **a** Model 1, generated through the cloth simulation; **b** model 2, generated through the rigid body simulation. Reproduced from reference [47] with the permission of the authors

in the protection, preservation, and dissemination of heritage clothes.

Historical clothes with unknown original appearances

As mentioned before, unearthed historical clothing usually suffers from various degrees of damage. Apart from clothing objects, the clothing culture for specific countries or cultures can also be recorded and revealed by historical paintings, photos, murals, pottery figurines, documents, and some other carriers. In these cases, the digital reconstruction of historical clothing would be more complicated, for the original appearance of historical clothing and the relationship between clothing and people are unknown. Accordingly, it is necessary for the researchers to have abundant knowledge, rich experience, and professional skills to replicate the original appearance of historical clothing as much as possible.

The historical clothing recorded in ancient paintings or books is an important prototype for digital reconstruction. In recent years, many scholars have been committed to reconstructing the historical clothing presented in ancient Chinese murals and paintings. The style, structure, and color of historical clothing shown in the murals and paintings can provide necessary basis for generating a preliminary 3D model, while the archaeology of historical clothing can provide necessary information for further reconstruction. For example, by using the similar 3D–2D–3D method in Ref. [45] mentioned before, Liu et al. [48] successfully extracted the pattern blocks from murals of the Tang tomb in China and realized the digital reconstruction of the corresponding historical clothing, as shown in Fig. 7. In addition, similar digital reconstruction works were also conducted on historical clothing in the handed-down paintings such as the *Han Xizai Banquet painting* [38], the *DaoLian Painting* [49], the *Spring Outing Painting of Madam Guo* [50] and so on. In particular, based on detailed analysis and understanding of various costume-related artifacts such as real objects, paintings, and murals, Liu et al. [15] carried out a systematical 3D digital reconstruction of representative historical clothing belonging to 10 different dynasties of China, which clearly revealed the historical development of Chinese ancient costumes.

In the digital reconstruction process of historical clothing with an unknown original appearance mentioned above, attention was mainly focused on clarifying the proper style, pattern blocks, structure, size, fabric, decorative pattern, and color of clothing. However, the manufacturing technology of clothing in the old days would be quite different from that in the present day. Therefore, the possible influence of old technology on the digital reconstruction of historical clothing should also be taken into consideration in specific cases. Zhang et al. [53] noticed that shoulder pads, sleeve heads, and interlining were used to adapt the shape of frock coats in the past, and meanwhile, the silhouette of the coat reconstructed in CLO3D could be more fitted to the avatar with due consideration to these objects. Kuzmichev et al. [8] developed a method to parameterize the historical pattern blocks of men's suits and identify the hidden fabric deformations in historical pattern blocks caused by steam pressing. By calculating the fabric deformations quantitatively and modifying the pattern blocks accordingly, the digital reconstruction of a historical men's suit painted on the Prince Albert of Saxe-Coburg and Gotha's portrait was conducted more accurately, proving a high adequacy between the historical prototype form painting and the virtual 3D model [8]. In another work of Kuzmichev et al. [51], the structural information of 36 historical trousers published from 1822 to 1898 was also parameterized so as to generate corresponding 2D pattern blocks automatically in AutoCAD software. The 2D pattern blocks were further modified by taking into account the shrinking and stretching of fabrics originating from the moisture-heat treatment, and then the virtual 3D models of these trousers were reconstructed in CLO3D software. Figure 8 shows the imitation of moisture-heat treatment in the computer reconstruction of trousers. By comparing the reconstructed 3D models of trousers with and without moisture-heat treatment (Fig. 8b, c), it can be demonstrated that the wrinkles can be eliminated by taking the fabric deformations into account.

Besides, there are some specific cases in which the digital reconstruction of historical clothing is much more complicated. In addition to the structure, fabric, color, pattern blocks, and manufacturing technology of clothing to be reconstructed, the interaction between clothing and specific objects, the interaction between the clothing of outer layer and inner layer, or some other aspects, may also have a noticeable effect on the reconstruction process and result. For instance, Kuzmichev et al. [54] carried out the digital reconstruction of late Victorian riding skirts according to pictures of riding habits published in 1887. The "horse–avatar–riding habit" virtual system was generated in CLO3D software to find the pressure points that reflect the contact between the avatar and the riding skirts. These pressure points were used to control the virtual try-on of the riding skirt by the function "tack on avatar" of CLO3D [54]. In this way, the interaction between the horse and riding skirts is fully considered, and the corresponding reconstructed skirts are in exact accordance with prototypes in historical pictures of riding habit. Moskvin et al. [36] developed a method to build the virtual replicas of a multi-layer costume from the 1860s, which consists of drawers, a chemise, crinoline, petticoat, lining, and skirt. Three

Fig. 7 Reconstruction of historical clothing in murals of the Tang Tomb in China. Reproduced from reference [48] with the permission of the authors

possible 3D models with different underskirt layers, i.e., model 1 (drawers + chemise + crinoline + skirt), model 2 (drawers + chemise + crinoline + petticoat + skirt), and model 3 (drawers + chemise + crinoline + petticoat + lining + skirt), were generated in CLO3D, and the result is shown in Fig. 9. According to the comparison of overlapped contours shown in Fig. 9d, it is indicated that the highest consistency between the prototype and the reconstructed costume (model 3) can be achieved when the interaction between skirt and underskirt layers is considered properly.

In a word, the digital reconstruction of historical clothing with an unknown original appearance is a very complicated work in which all aspects affecting the reconstruction results should be well considered, such as style, size, fabric, color, pattern blocks, manufacture technology, clothing–clothing interactions, clothing–object interactions, and clothing–human interactions. Nevertheless, the digital reconstruction of historical clothing with an unknown original appearance is a very important work, for it would make a great contribution to the restoration of the appearance of historical costumes, the

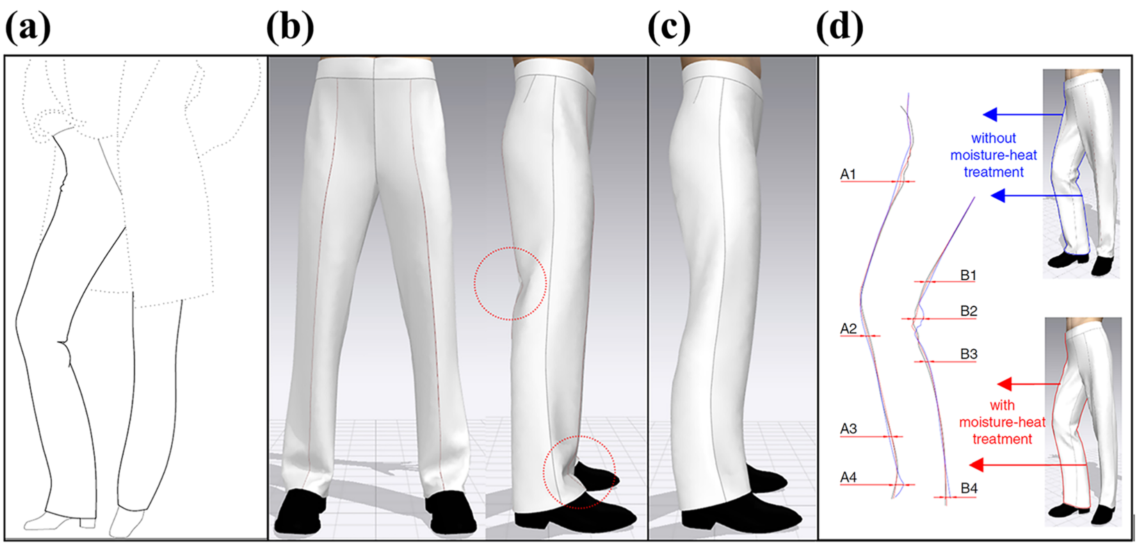

Fig. 8 Imitation of moisture-heat treatment in computer reconstruction of trousers. **a** The shape of the object of reconstruction; **b** 3D models of trousers without moisture-heat treatment; **c** 3D models of trousers with moisture-heat treatment; **d** parameters deviation used to compare historical and reconstructed trousers displayed. Reproduced from reference [51] with the permission of the authors and Emerald Publishing Limited

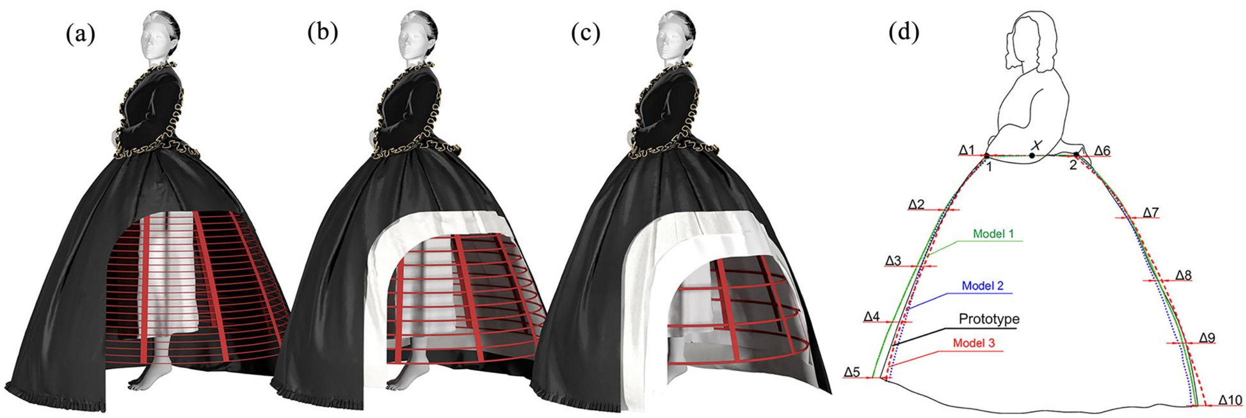

Fig. 9 Digital reconstruction of a multi-layer costume (cage crinoline and skirts) from the 1860s. **a** Model 1; **b** model 2; **c** model 3; **d** overlapped contours of model 1, model 2, model 3 and prototype. Reproduced from reference [36] with the permission of the authors and Taylor & Francis

dissemination of costume heritage, and the establishment of digital clothing museums.

Discussion and future directions

The development of digital technology has greatly changed the ways to restore and reconstruct heritage costumes. However, this is an arduous task full of various challenges. This section, which focuses on the digital reconstruction process, will delve into the specific challenges that require resolution. Besides, the application of digital methods in displaying restored and reconstructed heritage costumes, and future directions for digitizing heritage clothing will also be discussed briefly.

General steps in the reconstruction process

According to section "3D virtual reconstruction of heritage clothing", it can be summarized that the digital reconstruction of heritage clothing mainly involves the following three steps:

Step I, collect and analyze the initial data. Before reconstructing historical costumes, large sets of initial data need to be collected, including the size, structure, fabric, color, decorative pattern, pattern blocks of costumes, manufacturing technologies, body measurements, and so on. These data can be extracted from various sources, such as historical books, archives, pictures, ancient paintings, murals, museums, or private collections. For example, to reconstruct the riding skirts presented in historical pictures, Kuzmichev [54] analyzed the rider's position, sizing systems, body measurements, pattern drafting methods, pattern blocks of "shaped" riding skirts from 15 books, and the relationship between pattern blocks and body measurements. In another instance, based on collected costume materials and archaeological documents, Liu et al. [15] conducted a detailed analysis of the styles, colors, patterns, and fabrics of ancient Chinese costumes before corresponding reconstruction. It is worth noting that relevant data should be verified carefully to ensure the efficiency and accuracy of this step.

Step II, carry out digital modeling using computer technologies. This step aims to create 2D models of pattern blocks and 3D models of historical bodies and costumes based on the initial data compiled in Step I. As indicated in Fig. 2, three primary methods are commonly used in the digital reconstruction of clothing, i.e., 3D scanning, 3D modeling, and 3D virtual try-on. All of these methods cannot be done without the participation of computer modeling in professional software, including the processing of scans in Artec Studio [44], parameterization of shape, construction, and pattern blocks of historical skirts in AutoCAD [36], generation of avatars in CLO3D and Marvelous Designer [54], generation of parametric 3D models of skirts in Autodesk Inventor [36], virtual fitting, fabric properties setting, color setting, and decorative pattern setting in CLO3D [15], among others.

Step III, evaluate the reconstruction results. All factors involved in Step I and Step II can affect the reconstruction results. Therefore, the evaluation of reconstructed costumes is of significant importance. The ways to evaluate the reconstruction results adopted in previous studies can be divided into objective and subjective methods. Typically, the objective methods are conducted by comparing the contours of digital replicas with their prototypes (see Figs. 8 and 9), while the subjective methods are carried out in the form of questionnaire surveys.

Generally, the above three steps are applied to each aspect of historical costume reconstruction, including basic aspects such as (1) anthropometric data, (2) construction, (3) shape and size, (4) fabric properties, (5) color, and (6) manufacture technology, and unusual aspects in some specific cases such as (7) clothing–clothing interactions, (8) clothing–object interactions, and (9) clothing–human interactions. The execution of every step is inevitably faced with various challenges from all these different aspects. A good reconstruction work should take full consideration of each aspect and propose effective methods to deal with specific challenges arising from the features of specific garments. This point will be further discussed in section "Specific challenges in the reconstruction process".

Specific challenges in the reconstruction process

First, taking a particular aspect of garment reconstruction, i.e., human body measurements, as an example, it is essential to establish a historical mannequin before replicating the 3D fitting effect of historical clothing. However, the task of restoring the human body data of archaeological costume wearers is challenging due to the relative lack of adequate and accurate anthropometric data about historical bodies. It is widely known that anthropometric data plays a significant role in the 3D reconstruction of historic clothes. Improper original body sizes used to generate avatars may cause wrinkles, folds, and squeezes on reconstructed costumes [55]. On the one hand, the human body surface is a very complicated 3D profile whose parameterization requires dozens of indexes [8]. If the avatar is built with an insufficient number of indexes, the digital avatar could show a significant difference from the actual human body [56]. In the practice of reconstructing historical clothing, one may find that the number of indexes provided by reference sources is very limited. On the other hand, many of the anthropometric data recorded in archives were usually measured on male or female bodies wearing shirts, trousers, and so on [53]. That is to say, this type of body size measurement may not be accurate enough, as it includes measurements of the naked body, fabric thickness, and air gaps.

For the above reasons, there are still many obstacles in the initial data collection (Step I mentioned before) of anthropometric measurements. In previous studies, many efforts have been made to overcome these obstacles. For instance, in reconstructing men's full-dress suits from the nineteenth century, Kuzmichev et al. [8] utilized relevant data from the historical sizing table of the vest as body measurements to generate an avatar, for the vest was a close-fitting garment with small ease and closer to the nude body measurements. Zhang et al. [52] devised a method to extract more anthropometric indexes from 47 pattern blocks published between 1891 and 1913 by figuring out how pattern block parameters, body measurements, and ease allowance were related. In another work, Zhang et al. [57] showcased the way to obtain anthropometric data about the male body of the 1740s based on a combination of pattern blocks, pictures of historical costumes, and virtual simulation. Besides, in some cases, more indexes are needed owing to the complexity of historical costumes to be reconstructed. To reconstruct the digital twin of the female wearing a corset and skirt with a crinoline, Kuzmichev et al. [58] used historical body dimensions from sizing systems and added new dimensions extracted from authentic historical corsets and crinolines. Additionally, body postures, which may also be a crucial factor in reconstructing some specific historical costumes, need to be parameterized with additional indexes. For example, Kuzmichev et al. [54] obtained body measurements in mounted and dismounted positions based on images dated 1887, authentic pattern blocks, and the relationship between pattern blocks and body measurements. It should be noted that the sources of anthropometric data in the works mentioned above are mainly historical sizing tables and pattern blocks recorded in manuals, books, and pictures of the nineteenth to twentieth centuries, possibly due to the formation of basic principles of human body measuring in the apparel industry during this period. All in all, these studies have indeed shown some successful cases of obtaining proper anthropometric data through various methods.

When reconstructing historical clothing much earlier than the eighteenth century, sources of anthropometric data such as sizing tables are very limited. Archaeological remains can serve as meaningful sources of body dimensions under this circumstance. By measuring mummies and buried corpses, it is possible to obtain ancient human data, such as body height. However, it should be noted that the muscle and adipose tissues of archaeological remains are decreased in size due to dehydration (mummies) and decomposed due to putrefaction (buried corpses). Therefore, only a few body data of ancient people could be extracted. Apart from archaeological remains, statues or figurines are also important objects that record the shape of human bodies. It provides another potential way to obtain body measurements, including the body height, the height from bust to floor, the height from hip to floor, the distance between bust and waist, and the widths of bust, waist, and hips [59]. However, the accuracy of the obtained anthropometric data is greatly affected by the dimensional ratio of the statue to the actual body, the possible presence of ”obstacles” like the garment of the statue, and the body postures of the statue. Generally, the body dimensions obtained from archaeological remains and statues are insufficient. Further research is required in this field to obtain adequate and accurate anthropometric data by incorporating new sources and processing methods.

The lack of anthropometric data may also raise challenges in the digital modeling procedure, i.e., Step II mentioned in section "General steps in the reconstruction process". Moskvin et al. [56] presented a systemic method to obtain a complete anthropometric database for the purpose of establishing the 3D digital model of nineteenth century dress forms. Based on the hypothesis that the body dimensions reflected by dress forms were constrained by the corset, this method was conducted by combining the historical sizing tables and the historical corsets, allowing a determination of 43 anthropometric indexes. 34 indexes were adopted from relevant manuals, while the additional 9 indexes were measured from reconstructed corsets to give a more accurate description of cross-sections of the bust, waist, and hip. The parametric dress form built in Autodesk Inventor using these 43 indexes was evaluated as a more adequate digital replica of the prototype when compared with avatars generated by MakeHuman, CLO3D avatar, and LookStailorX using 11 indexes [56]. That is to say, an adequate amount of body measurements is necessary for the generation of an avatar with high accuracy. Besides, relevant challenges in the evaluation of reconstruction results will be further discussed in section "Criteria for validating the results of restoration and reconstruction".

Next, focusing on another aspect of historical costume, i.e., the color, there are also many challenges caused by this aspect in the virtual reconstruction process. Relevant challenges regarding the color of the garment mainly emerge in the collection and analysis of initial data (Step I mentioned in section "General steps in the reconstruction process"). Historical costumes, especially unearthed ones, often suffer from severe fading owing to natural aging, stains and pollution, microbial action, and other environmental factors. Therefore, confirming the original color of historical clothing is very difficult.

Thanks to the development of contemporary analytical instruments, it is possible to determine the original color of faded textiles by detecting and analyzing the remains of dyes. Microspectrofuorimetry, coupled with high-performance liquid chromatography (HPLC) methods, enables the identification of sources (such as cochineal-based, madder-based, or others) and formulations used for dyeing the ancient Andean textiles [60] and knitted caps (fifteenth to sixteenth centuries) [61], allowing the reveal of technology in the preparation of used colors. Scanning electron microscopy (SEM) equipped with energy dispersion X-ray spectrometry (EDS) is capable of analyzing the color of historical textiles by providing information about the elemental composition of non-metallic substances such as mordant used with dyestuffs [62] and metallic threads used in some textile artifacts [63]. Multispectral imaging (MSI) techniques are possible to indicate the presence of colorants, such as indigo, madder, tannins, or mixtures [64]. Except for the application in historical textiles, the above analysis techniques were also applied to investigate the original color of murals which also contain plenty of information about historical clothing. For example, Chai et al. [65] determined the pigment distribution and reconstructed the original color of a faded mural of Northern Wei Dynasty by a combination of MSI, SEM–EDS, HPLC, digital microscope, and other modern analysis techniques. With the aid of X-ray fluorescence analysis, Fourier-transform infrared spectroscopy, and polarized microscopy, Philippova et al. [66] investigated the influence of temperature on color change for the main pigments of Old Russian murals to digitally reconstruct the original color. In general, contemporary analytical instruments make it possible to identify the dyes of textiles and the pigments of murals, providing powerful support for overcoming the challenges of reconstructing the original color of historical costumes.

In addition to the above experimental methods, documentary evidence, such as existing historiography and archaeological research on costume, could serve as important sources of color reference in the 3D reconstruction process. For instance, the original color of an unearthed costume from Mawangdui Tomb was ascertained by a combination of archaeological knowledge about the tomb's owner (the wife of an emperor's official) and historiography knowledge about the color of the official costume [45]. In Liu et al.'s work on costume reconstruction [15], a systematic analysis was made to explain popular colors in different Chinese dynasties based on five basic colors related to the five elements (metal, water, wood, fire, and earth) and unique characteristics of each dynasty. It is worth noting that, to enhance the credibility of original color indicated by a documentary method, it would be much better to do the triangulation of data. Data triangulation involves a range of evidence that is provided by various sources and investigative methods and cross referenced rigorously [67]. On account of this point, the original color of historical costumes should be reconstructed by referring to different sources, such as relevant physically repaired relics, ancient paintings, objects from the same period, and so on. Besides, the costume color determined by the experimental methods mentioned above can also be integrated for data triangulation, which is expected to provide a more plausible determination of original color information.

In short, the digital reconstruction of various types of heritage costumes should not rely on a single source like an unearthed historical costume or a specific picture of a mural. A much more comprehensive reconstruction can be made by combining various sources to enrich the initial database of each aspect of historical garments.

Criteria for validating the results of restoration and reconstruction

At present, there is still a lack of uniform methods and criteria for validating the accuracy of restored or reconstructed costumes. For this reason, sometimes it may be hard to say whether the restored or reconstructed results are satisfactory enough, especially when it comes to the reconstruction of historical clothing with unknown original appearances.

To be specific, in the case of digitally restoring damaged clothing-related archaeological heritage, the practice for evaluating restoration accuracy is comparatively mature. Peak signal-to-noise ratio (PSNR) and structural similarity (SSIM) have been widely employed as evaluation metrics to compare the results obtained by different restoration algorithms, such as in reference [9, 10, 21, 23, 26]. A higher PSNR or SSIM value indicates a more valid restoration algorithm, as well as greater restoration precision.

Compared with the above-mentioned digital restoration methods dealing with 2D images, it will be more complicated when evaluating the accuracy and effectiveness of 3D clothing reconstruction methods. As for the digital reconstruction of heritage clothing with known original appearances, the reconstruction accuracy can be evaluated by comparing the contours of the originals with their digital replicas. For example, Wijnhoven et al. [47] validated the reconstruction accuracy by overlapping the contours of the actual Vimose coat and the digital one. This is also a common and effective practice in reconstructing historical clothes with unknown original appearances, as shown in cases of riding skirts [54], nineteenth century trousers [51], and historical skirts [36]. However, this validating method has the following limitations: (1) usually, only the front or back contour could be provided by the originals (displayed in museums with windows) or prototypes of historical clothes. In this situation, it is difficult to guarantee that the 3D reconstruction is accurate enough in other directions or dimensions. That is to say, accuracy evaluation by comparing contours may not be very persuasive. (2) The comparison of contours is able to reflect whether the overall shape of historical costumes is reproduced properly. However, aside from shape information, the color, fabric, style, and size of historical clothing are also crucial for 3D reconstruction. Although these aspects are usually taken seriously in the reconstruction process, their accuracy cannot be validated by comparing contours. (3) Many of the historical prototypes used for 3D reconstruction in related works do not show exact contours, especially those with unknown original appearances, such as Chinese costumes recorded in ancient paintings [15]. Considering all these points, one may conclude that the contour comparison method is not applicable in evaluating overall 3D reconstruction accuracy, including shape, color, fabric, style, size, and other aspects of historical costumes. To overcome this obstacle, analytic hierarchy process (AHP) and fuzzy AHP methods were adopted in some works [45, 50, 68] to evaluate the visual reconstruction accuracy of garments from multiple aspects. However, the AHP and fuzzy AHP methods involve the conduct of questionnaire surveys and thus strongly depend on the number of questionnaires and the background and experience of participants. In other words, the drawbacks of AHP or fuzzy AHP methods are notable, i.e., non-quantitative and a certain degree of subjectivity. Therefore, the AHP or fuzzy AHP method may be a feasible but not ideal method for 3D reconstruction evaluation of historical garments. In summary, there is still a lack of uniform evaluation criteria and methods for the accuracy of digitally reconstructed costumes.

The application of digital methods in displaying restored and reconstructed heritage costumes

The digital restoration and reconstruction of heritage costumes is beneficial for establishing online display systems and virtual museums of historical clothing, inheriting ancient costume culture, as well as promoting the dissemination of heritage clothes. By applying modern technology to represent and visualize heritage clothing, a wider group of recipients can reach out traditional clothing and have a better understanding of the culture behind the clothes.

The great significance of virtually displaying heritage clothing has attracted much attention from museums and universities, driving them to collaborate with Internet technology companies and develop online display systems to virtually showcase their collections of digital textiles and historical clothing in a 2D manner. For instance, Google company, in partnership with 183 cultural institutions including the Victoria and Albert Museum, the Metropolitan Museum of Art, and the China National Silk Museum, launched the ”We Wear Culture” project to present a large number of digital replicas of historical clothing on the web pages of Google Arts & Culture [45]. Besides, similar projects were also conducted by Vassar College, Drexel University, Ohio State University, and Ryerson University to show the public good examples of the preservation, enhancement, and adaptation of cultural heritage [36]. Generally, these projects provide good examples of the application of 2D digital methods in the virtual display of clothing.

With the rapid development of 3D digital technologies, the establishment of 3D virtual museums is thriving in various fields. The restored or reconstructed 3D costumes can be displayed by various online VR museums, showing different costume cultures of different nations more conveniently. Obviously, the VR museums open up a brand new field for future generations to preserve tangible and intangible heritage costumes, and to deepen the understanding of heritage clothing. Many scholars have attempted to construct small-scale digital archives of historical clothing in the form of 3D virtual displays. For example, Hisatomi et al. [69] developed a 3D archive system for Japanese traditional performing arts that can present Japanese traditional costumes for performances in 3D multi-view video. Meier et al. [70] made an effort to create a fully virtual museum of Spanish clothing from the sixteenth century with a 360° view of each garment, enabling the public to visit the virtual museum closer to a real museum. With the aid of VR technology, Lei et al. [71] built a digital clothing museum to restore and present the Yi nationality costumes of China. Based on the collections of the National Costume Museum of Beijing Institute of Fashion Technology, Shang et al. [72] designed and implemented a virtual costume museum to achieve a more realistic 3D dynamic display effect. Jiang et al. [68] developed an interactive multimedia system for the digital protection and inheritance of Chinese traditional costumes based on VR and AR technology.

It is worth noting that, compared to the above works in which the digital replicas are usually presented in a static form, motion capture technology provides a different way to display historical clothing dynamically. Dvořák et al. [6] conducted a very interesting work to digitally display historical clothing in motion via two innovative applications, i.e., Virtual Wardrobe, which allows the 3D presentation of clothing replicas with a true-to-life simulation of movement, and Virtual Mirror, which allows visitors to virtually try-on the historical clothing directly themselves with the aid of a motion-sensing device. Ami-Williams et al. [73] presented the application of motion capture technology for acquiring the movement of dance performers wearing traditional African masquerade garments.

Future directions for digitizing heritage clothing

It can be seen that the way to digitally restore and reconstruct clothing-related cultural heritage will be more intelligent and efficient in the future. Computer algorithms such as deep learning have already been introduced into the identification of clothing images. Various deep learning models have been developed in recent years, such as CNN, GAN, deep belief network (DBN), and recurrent neural network (RNN) [74, 75]. As mentioned in section "Digital restoration of damaged clothing-related archaeological relics", the GAN model is frequently used in restoring damaged regions of clothing images. Meanwhile, clothing-related research based on CNN also shows an increasing trend involving a wide range of fields such as clothing image recognition and classification [76, 77], clothing image retrieval and recommendation systems [78, 79], clothing feature extraction and measurement [80], and so on. For example, Nawaz et al. [79] put forward a method to automatically classify the traditional national costume pictures of Bangladesh by using the CNN algorithm, which can be applied to e-commerce platforms. Wang et al. [80] proposed a method to identify key points and automatically measure dimensions of Han-style costumes based on CNN, which solved the problem that there was little data provided to researchers in ancient costume archaeological reports. These studies provide new ideas for further introducing computer technologies into the restoration and reconstruction of heritage costumes. With advances in digitization technology, the measurement, classification, and restoration of costumes can be more automatic in the future. On this basis, more original data of traditional costumes is expected to be acquired, which will provide a richer source of data triangulation for digital reconstruction steps and, in turn, assist the digital reconstruction process.

At the same time, the exhibition form of digital costume archives will be richer, and the user interface will be more attractive and easier to operate. During the on-site visit to the museum, the application of AR and VR has already pulled in the distance between audiences and cultural relics. These relics can be perceived and touched by the audience in the virtual space, thus deepening people's understanding of their cultural connotations. In the future, the application of various 3D digital technologies in displaying historical costumes will become more and more popular. Meanwhile, more types of digital technology will be introduced to the management of heritage clothes. For example, by applying the knowledge graph in the management of digital cultural heritage, the historical background and stories related to each cultural relic can be displayed, which will provide a more accessible, inclusive, and personalized experience for users with different interests. In addition, the knowledge graph can help museums better understand the relationship between cultural relics so that museums can manage cultural heritage collections more efficiently [81]. Generally speaking, the increasing 3D digital preservation and display of heritage clothing is the apparent development trend. It can be expected that more and more professional institutions and scientific research institutions will devote themselves to establishing 3D databases and online interactive display platforms for costume heritage. In the future, dynamic display, interactive behavior, and user experience will be further emphasized in the virtual display of historical clothing.

Conclusion

In this paper, previous studies on digital restoration and reconstruction of heritage clothing are reviewed. Aiming to reveal the significant application of digital technology in the preservation and inheritance of heritage costumes, this paper summarizes recent progress in the digital restoration of damaged clothing cultural relics, and the general steps and several special circumstances of 3D digital reconstruction of heritage clothing. The main conclusions are summarized below.

(1) The digital restoration of damaged clothing-related archaeological relics, including the damaged archaeological costumes and fabrics, and the damaged clothing images in archaeological murals, can be conducted with the aid of various digital image inpainting methods, such as geometry-based methods, patch-based methods, and deep-learning-based methods. More attention should be paid to this field, for it would greatly assist in the further 3D digital reconstruction of clothing and enrich the database of heritage clothing.

(2) The digital reconstruction of historical clothing objects, either by replicating existing objects or by remaking objects that don't actually exist, is a very complicated and important work. The reconstruction results can be affected by various aspects, such as style, size, fabric, color, pattern blocks, manufacturing technology, clothing–clothing interactions, clothing–object interactions, and clothing–human interactions. All these aspects should be carefully considered in the reconstruction process of heritage clothing.

(3) The way to display restored and reconstructed heritage costumes is greatly expanded by digital methods such as VR, AR, and motion capture. Various institutions and universities are devoted to developing virtual museums, which make significant contributions to the preservation of historical clothing and the dissemination of traditional clothing cultures of different nations.

(4) Several challenges, regarding the relative lack of adequate and accurate anthropometric data, the restoration of the original color of faded historical clothing, and the lack of uniform methods and criteria for validating the accuracy of restored or reconstructed results, are identified. Further efforts are required to address these challenges and extend the application of digital technology in the preservation and dissemination of heritage clothing.

Abbreviations

TCH	Tangible cultural heritage
ICH	Intangible cultural heritage
3D	Three-dimensional
2D	Two-dimensional
VR	Virtual reality
AR	Augmented reality
CNN	Convolutional neural network
GAN	Generative adversarial network
CT	Computed tomography
PSC	Patch structure complexity
UNESCO	United Nations Educational, Scientific and Cultural Organization
HPLC	High-performance liquid chromatography
SEM	Scanning electron microscopy
EDS	Energy dispersion X-ray spectrometry
MSI	Multispectral imaging
PSNR	Peak signal-to-noise ratio
SSIM	Structural similarity
AHP	Analytic hierarchy process

DBN Deep belief network
RNN Recurrent neural network

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