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APPLIED RESEARCH

Workflow for Creating Animated Digital Replicas of Historical Clothing

JIŘÍ KUBIŠTA[1], OLDŘICH LINHART[1], DAVID SEDLÁČEK[2], AND SVEN UBIK[1], (Senior Member, IEEE)
[1]CESNET, 160 00 Prague, Czech Republic
[2]Faculty of Electrical Engineering, Czech Technical University in Prague, 160 00 Prague, Czech Republic

Corresponding author: Sven Ubik (sven.ubik@cesnet.cz)

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ABSTRACT Preserving and presenting historical clothing items in museum collections is challenging due to their sensitivity to handling but of great importance due to their deterioration over time. Creating digital replicas of these items can give museums unique documentation and presentation possibilities. A specific workflow is needed to create 3D digital models that can be simulated in real time to present clothing objects in motion and a realistic environment. This paper presents a detailed description of the workflow to create realistic 3D digital models of historical clothing items for motion animation. We demonstrate the use of the workflow on clothing items from the Prague City Museum's collection.

INDEX TERMS 3D reconstruction, photogrammetry, clothing digitization, animated clothing.

I. INTRODUCTION

Many museums have valuable collections of historical clothing items. Textile materials are generally more sensitive to handling and deteriorate more quickly over time than other materials. A specific characteristic of clothing collection objects is that they are best observed as people wore them, including the movements of the fabric.

Therefore, creating digital replicas of historical clothing items makes sense to preserve their appearance and characteristics for future generations and allow them to be presented in a life-like environment.

Digitizing textile collection objects and presenting them in real-time animations requires a specific process that is different from digitizing other types of collection objects.

II. RESEARCH AIMS

Our goal was to design a workflow for creating realistic 3D digital models of historical clothing items allowing their simulation in motion. Various useful applications exist for such digital content, including:

- Virtual wardrobe that allows users to inspect precious collections of textile items without physical handling
- Virtual mirror that uses a motion-sensing device to allow people to see themselves wearing a digital copy of a textile collection item
- Using historical clothing for game animations and other virtual reality environments

The key novelty of our work is the extension of traditional 3D solid reconstruction techniques based on photogrammetry to support clothing visualization in dynamic motion using commonly available tools.

We select the parts of the process that need to be extended with additional tools and link them by data paths. We will demonstrate the proposed workflow with selected museum clothing collection objects.

While this article focuses on obtaining such a model in sufficient quality, the actual form of presenting these models in motion is described in article [1].

We refer to the previous work in section III. We present an overview of our approach and list the tools that we have chosen to use for the workflow in section IV. We describe the individual steps of the proposed workflow and show solutions to the problems we encountered in section V. Next, we present the results of digitizing the selected clothing objects from the Prague City Museum's collection in section VI. We discuss the limitations and possible future

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improvements of the proposed approach in section VII. Finally, we draw conclusions in section VIII.

III. RELATED WORK

Some museums and institutions present parts of their clothing collections online, mostly using 2D photographs. We wear culture[1] is part of the Google Arts and Culture project, showcasing partner institution collections. Photographs of clothing items are included in a series of storytelling articles. Institutions that present their clothing collections online in 2D photographs include The Metropolitan Museum of Art,[2] The Victoria and Albert Museum,[3] The National Museum of American History[4] or The Kyoto Costume Institute.[5]

Methods based on 3D laser scanning and photogrammetry have proven to be useful for preserving information about the surface form of historical artifacts [2], [3], [4]. Photogrammetry is referred to as a process that uses a combination of computer vision methods referred to as SfM (Structure from Motion) and MVS (Multi-View Stereo) [5], where multiple color photographs of an object are taken and used to calculate the surface of a 3D digital model.

In photogrammetry, a detailed surface color or texture record is often cited as an advantage. In contrast, optical scanning is more appropriate for objects where we are more interested in the accuracy of shape than in the resulting color reproduction [3], or where surfaces contain few textural features, such as porcelain, which present a problem for photogrammetry because it relies on existing light patterns. An important factor is that even good-quality cameras are usually less expensive than optical scanners.

Therefore, various techniques in the literature focus on suitability for specific reconstructed objects. Many articles deal with the recording of archaeological remains [6], [7] where the use of these methods in the cultural heritage field began. We can also see methods for other types of objects of different properties and sizes, such as buildings, palaces, and sculptures [3], [8], [9], underwater sites [10], skeletal remains [11], everyday objects [12], [13], up to small objects such as insects [14]. These presented procedures are mostly based on a commonly used workflow that can be summarized in the following steps: taking photos, calculating a detailed 3D model, optimizing the model concerning the target presentation, and creating textures for the model [15].

Most of these procedures assume solid bodies, which is unsuitable for the 3D reconstruction of clothing. With the development of deep learning methods, procedures for digitizing dynamically changing objects such as moving people and animals are also emerging [16], [17]. Unfortunately, the quality of these reconstructions is inadequate compared to previous methods in terms of accuracy and even color fidelity [18].

In terms of the literature on 3D clothing models and their presentation, a review focusing on the digitization of historical garments was presented in [19], although it focuses on the use of 3D scanners. A short article [20] summarizes several practical textile digitizing projects undertaken by museums that use photographs or rotating models to present digitized collection objects. In [21] is described 3D photogrammetry workflow for digitizing museum fashion collection in the static form. Creating a 3D model of a garment using the Autodesk 123D Catch software with markers placed on the garment was described in [22]. Scanning the 3D relief of the embroidery is described in [23]; the model is then used to apply the decoration to other pieces of fabric, in [24] the authors focus on capturing realistic colors of the textile collection objects.

Other methods focus more on modeling replicas of clothes than recording them. A method to characterize the exact dimensions of historical skirts based on their 2D images and a known multi-layer structure and thus create their numerical replicas that allow for future 3D visualization was described in [25]. In articles [26], [27], [28], authors analyze the conserved ring armors and build models composed of individual rings to calculate the dynamic behavior of the whole armor in the game engine. In recent years, there have been significant advances in the efficiency of algorithms for textile simulation [29], [30], [31], which focus on the details of the simulation, even though they do not usually operate in real-time.

When creating digital models with rich textures, the quality of UV unwrapping, that is the mapping of 3D model's surface onto 2D images, is important. The solution in paper [32] uses two methods. The first method uses laying out the clothing on a flat surface and copying the contours of each piece with special adhesive paper. However, this is often not possible with sensitive museum objects. The second method uses a geometric projection of seams marked on photographs of the clothing from three different angles onto a 3D model to create virtual seams along which the model is divided into separate UV islands. This approach is difficult to apply to more complex shapes, such as with the self-occlusion of parts of the clothing.

A number of papers have investigated the creation of 3D models of human bodies. A method to obtain accurate 3D body models and texture of arbitrary people from a single monocular video of a person moving has been described in [33]. The creation of a 3D virtual mannequin using body dimensions obtained from front and side 2D photographs of a person was described in [34]. It can be envisaged that this method could be used to create 3D character models for digitized clothing presentations using pictures of the original wearer. A technique for precise capturing and animating skin deformation in human motion using a motion sensing system and many markers has been published in [35]. An overview article describing avatars in cultural heritage applications [36]

[1] https://artsandculture.google.com/project/we-wear-culture
[2] https://www.metmuseum.org/about-the-met/collection-areas/the-costume-institute
[3] https://www.vam.ac.uk/collections/textiles
[4] https://americanhistory.si.edu/collections/subjects/clothing-accessories
[5] https://www.kci.or.jp/en/archives/digital_archives

identifies dress as an important component reflecting the state of society at the time. It also points out that the dynamic qualities of dress are often under-represented, as seen, for example, in the case of traditional Malaysian women's dress in [37].

IV. MATERIALS AND METHODS

A. METHODOLOGICAL APPROACH

The proposed workflow for digitizing textile objects involves several steps described in section V. Four versions of the clothing model are created during the workflow:

1) *Photogrammetric model* - generated from a set of images in RealityCapture. In our case, this model has approximately one million triangles. The model often contains errors from photogrammetry (section V-B) and unwanted objects photographed (mannequins, pedestal, padding, etc.).
2) *High-poly processed model* - with environment elements removed and corrected photogrammetry errors, such as holes in mesh or texture. The complexity and topology of the polygon mesh are the same as for the *photogrammetric model*. Therefore, the number of triangles depends mostly on the parts removed from the model. Typically the number of triangles does not drop below half the original number.
3) *Rendered model* - rendered in the visualization application. It is decimated and retopologized and typically has a triangle count in the tens of thousands.
4) *Proxy model* - not rendered, but it is used to calculate the clothing movement simulation in Unreal Engine 5 and typically has a triangle count of several thousand.

We demonstrate the use of the workflow on clothing items from the collection of the Prague City Museum.

B. TOOLS

The tools that we used, their tasks in the proposed workflow, and their origins are summarized in Table 1. The reasons for selecting each tool are described in the following paragraphs. Where appropriate, we mention possible alternatives.

Reality Capture was used to create the initial 3D model based on photogrammetry because of high-quality results obtained from this tool in our previous projects [38]. However, any advanced photogrammetry software can be used. See the recent Open Source and commercial alternatives list in [5] - section II.

Blender was used for the elementary processing of the 3D model and as an intermediate step between the other tools. It was used for mesh decimation, editing UV maps and textures, checking the model topology and possible corrections, and for basic skinning of clothing on the created character. Blender was selected as a widely known open-source software for 3D modeling. Other 3D computer graphics software such as Maya, 3ds Max, or Cinema 4D can also be used.

MakeHuman is a free software used to create a 3D model of a character. Its advantages are highly configurable body proportions and the availability of user-created assets (e.g., for hair, shoes, etc.). Similar options are provided by the paid software Character Creator. Other alternatives are Daz 3D and the MetaHuman framework built in the Unreal Engine, which, however, have fewer options for configuring body proportions.

TABLE 1. Tools used in the workflow.

Tool	Tasks	Availability
Reality Capture	Creation of the initial 3D model using photogrammetry	www.capturingreality.com
Blender	Elementary processing of 3D models and an intermediate step between other tools	www.blender.org
MakeHuman	Creation of a 3D model of the character	makehumancommunity.org
Mixamo	Creation of a control skeleton and animations	www.mixamo.com
Marvelous Designer	Fitting clothing and the character	www.marvelousdesigner.com
Meshmixer	Correction of mesh errors and retopologization	www.meshmixer.com
Instant Meshes	Retopologization to uniform triangles	github.com/wjakob/instant-meshes
Unreal Engine 5	Rendering and clothing simulation in the Chaos physics system	www.unrealengine.com

Mixamo web service was used to automate the creation of a control skeleton for a humanoid 3D model. It contains a library of animations created using motion capture that can be downloaded and used to move a character. MakeHuman or other tools can also be used to generate a control skeleton. However, the resulting skeletons are incompatible with Mixamo's animations, which we wanted to use further in the workflow.

Marvelous Designer focuses on creating and editing digital models of clothing and accessories that can be used in games, movies, animation, fashion, etc. It primarily assumes the creation of clothing from scratch but can also work with imported models. We used Marvelous Designer to fit the clothing to the character in the base position. Although other software also includes fabric simulations (including Blender), Marvelous Designer is currently the winner in terms of simulation quality and computational efficiency.

Meshmixer was used to correct some mesh errors that can occur during photogrammetry and for mesh retopologizing so that the rendered model exhibited a more natural appearance during motion deformation in animation.

Instant Meshes is another mesh retopologizing tool, which we used to create the proxy model for motion simulation, composed of uniform triangles as much as possible. There are several retopologizing algorithms, and most 3D model editing programs, including Blender and Meshmixer, have this feature. However, their algorithms focus on preserving as much detail as possible, and the resulting model is typically not composed of uniform triangles, which is crucial for a quality clothing simulation.

Unreal Engine 5 was chosen for the final application because it currently provides the best quality rendering of complex scenes with a wide range of special effects. The second reason for its choice is its Chaos physics system, which provides high-quality real-time physical simulations such as clothing simulations.

V. PROPOSED WORKFLOW

This section describes the proposed workflow for creating dynamic models of textile objects and suggests solutions to potential problems. The sequence of the workflow steps is shown in Fig. 1. The points where the four versions of the clothing model are created during the workflow are marked (1) through (4) in Fig. 1. A more detailed structuring of the workflow into individual tasks is depicted in Appendix.

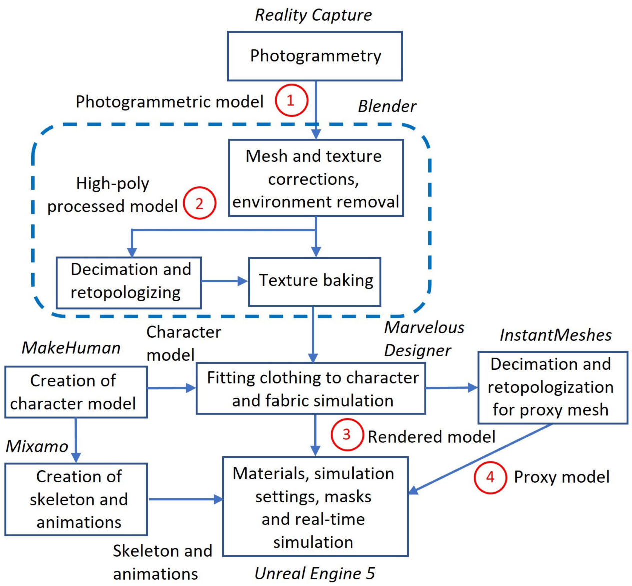

FIGURE 1. Workflow steps (the four model versions created during the workflow are marked 1 to 4).

The individual tools are well known. However, their specific use together in a workflow for creating 3D models suitable for physical motion simulation is new. The sequence of steps is as follows:

- An initial 3D model of the textile object is created using photogrammetry, similar to [15]. Its output is a highly detailed static 3D model with many polygons (see section V-A).
- The model usually requires mesh and texture corrections and removal of unwanted parts (see sections V-B and V-D).
- The model is decimated and retopologized for motion simulation (see section V-C).
- The character model for the clothing and its skeleton is created (see sections V-E and V-F).
- The clothing and character models need to be adapted to each other (see section V-G).
- The proxy model for motion simulation is created (see section V-H).
- Finally, the real-time motion simulation of the clothing and the character with a realistic appearance can be performed (see section V-I). External forces, such as wind action, can be included in the simulation.

A. PHOTOGRAMMETRY

Clothing items usually have distinctive textures. Therefore, photogrammetry is the preferred method for creating an initial static 3D model. It can easily find reference points in rich textures in photographs and typically captures textures better than optical scanning. However, specific properties of clothing items require some attention.

Extensive camera height changes - a tripod that can change the camera position from about 30 cm to 2 m is needed. We used a stand with a vertical shaft to move a tripod head quickly that can be disassembled and transported to the location of collection objects.

Round sleeves not touching - ideally, the top of the garment should be in a t-pose. If that is not permitted by a museum, the sleeves should not touch the body and should be filled to be as round as possible, rather than hanging down, creating a sharp cease.

A tall neutral background - clothing objects typically have a distinct vertical orientation. We usually need to capture the bottom of the clothing from below. Therefore, it is important to separate the top from the ceiling.

Light the background - in addition to lighting the clothing object, we also light the background so that it is slightly overexposed and easily removed by the photogrammetry software.

We used the Photorobot[6] turntable and software to remotely control the camera, lights, and turntable. A system similar to this speeds up the work when digitizing multiple objects, but its use is not necessary. A typical setup when capturing an object is shown in Fig. 2.

The size of the model computed by RealityCapture depends on the object, the number and the resolution of the photographs. For typical full-body clothing, the maximum model size that can be created ranges from 10 to 50 million triangles. For further processing, we export the photogrammetric model (1) at a resolution of 1 million triangles.

B. MODEL CORRECTION

After photogrammetry, elementary 3D model corrections may be required to create the high-poly processed model (2).

Scale and environment removal - the clothing object is typically placed on a mannequin, often created specifically for the object. The mannequin is digitized along with the textile object. This dummy and other auxiliary structures must be removed from the model. Similarly, some material at the ends of sleeves and other clothing openings must often

[6]https://www.photorobot.com

FIGURE 2. Photography of a textile object for photogrammetry - a tall background on the left, a stand for multiple camera positions on the right, lights for the object and for the background, the textile object in a near t-pose.

be removed. Removal is typically done in Blender by creating a simple model that fills an opening and then calculating the difference between the original and newly created model by a boolean operation. However, before the removal, the scale of the model should be adjusted based on the known dimensions of fixed elements, such as the mannequin or the rotating platform.

Minor errors - in parts of the clothing object with difficult access, such as under sleeves or with a bland texture, typically on dark fabric, the photogrammetry algorithm can create errors in the model. These usually appear as holes in the mesh or missing or spoiled texture. Extensive errors require the photogrammetry process to be repeated, focusing on the problem areas. Minor errors can be corrected by creating new geometry and applying texture from close areas or reference photos using Blender or Meshmixer as shown in an example in Fig. 3.

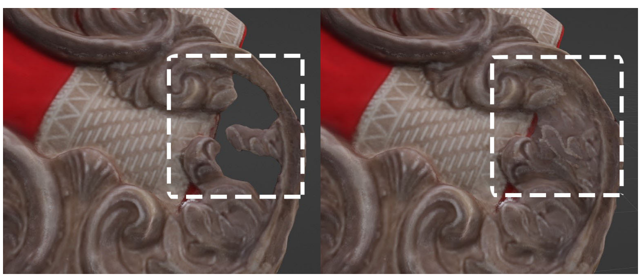

FIGURE 3. Correction of model errors after photogrammetry.

C. DECIMATION AND RETOPOLOGIZING

Mesh decimation - the physical simulation is computationally intensive and would not currently be possible to perform in real-time with a model of 1 million polygons. We save a copy of the high-poly model for later texture baking. We then use Blender to decimate the model mesh. Based on our experience with models of textile collectibles, decimating the mesh to 40 to 70 thousand triangles for each clothing layer is sufficient to preserve even the finest details of clothing in their presentation. The specific number needs to be estimated for the particular object.

Mesh retopologization - for the natural appearance of the model during character movement or due to the environment (wind), the mesh should be composed of equilateral triangles as much as possible. Narrow, elongated triangles can cause visual artifacts during movement and should be avoided. Therefore, a retopologizing of the model is needed.

We use the MeshMixer tool for this purpose. The two main modes are Relative Density, which tries to distribute the triangles uniformly, and Adaptive Density, which tries to preserve more detail where needed by creating a denser triangle mesh there. Adaptive density is the preferred mode for the rendered model. An example of the effect of retopologizing is shown in Fig. 4.

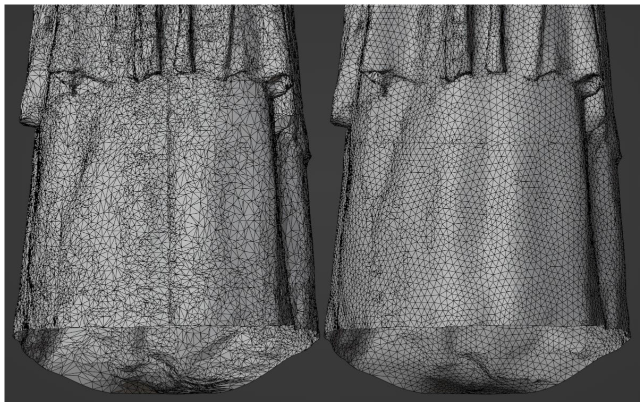

FIGURE 4. Model topology before and after retopologizing for the rendered model.

D. TEXTURES

Texture baking - a change in mesh geometry leads to a deformation of the texture that is mapped onto the model. A new texture should be mapped to the simplified mesh using a process called texture baking.

The UV map defines mapping between 3D and 2D space. In the UV mapping, the triangles should retain their relative size and shape from the 3D model as much as possible. However, keeping the triangles undistorted usually requires splitting the UV map into multiple islands, which means less efficient use of texture space.

Adjust UV unwrapping - we use Blender for UV unwrapping. A higher value of the Angle Limit parameter reduces the triangle distortion at the cost of creating more islands. Blender provides a visual clue as to how the triangles are distorted in the UV map, see Fig. 5. From left to right, it is the original texture, the color-coded distortion of triangle sizes, and the color-coded distortion of triangle angles. The distortion increases from blue to green to yellow, high distortions are orange to red.

Another problem is when triangles are too narrow, see Fig.6. Depending on the texture resolution, this can cause the patching algorithm to judge that there is no area/triangle mapped to such location in the UV map, as it does not cover

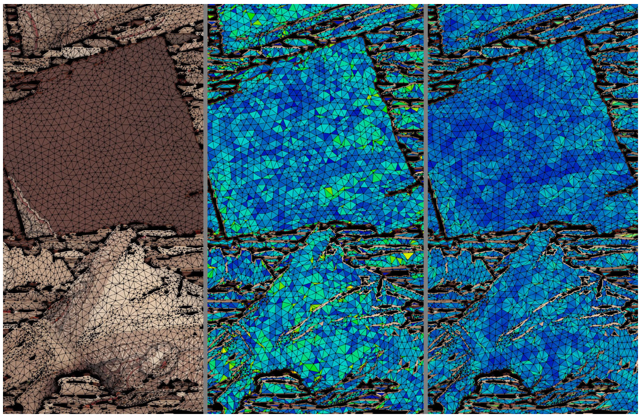

FIGURE 5. Visual cue to triangle distortion in UV unwrapping in blender.

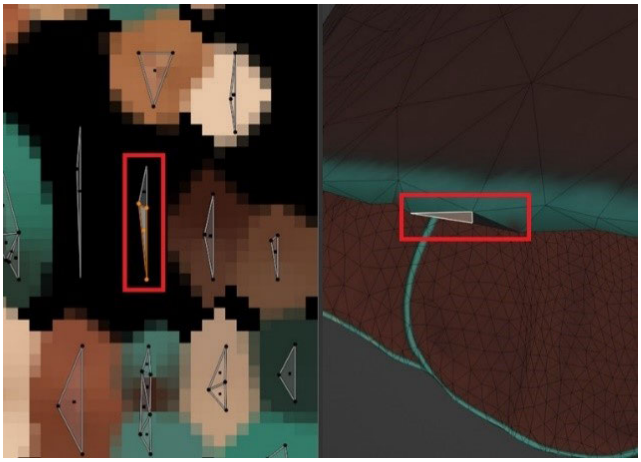

FIGURE 6. Very narrow triangles in the texture (left) and in the 3D model (right).

even one pixel of the texture, leaving some triangles without color. Similarly, if a triangle is not narrow in the mesh, but it is narrow in the UV map, it does not cover enough space in the UV map to accommodate all the necessary detail in the texture, and again this can create artifacts in the model. These problems should be solved by manually editing the UV map.

Adjust texture boundaries - when baking, we want the color area to extend slightly beyond the boundaries of the individual triangles by a few pixels. When displaying an object from farther away, additional levels of texture are generated with progressively lower resolution in a process called mipmapping [39]. If the colored portions of the texture were averaged with the black pixels behind the island boundary, artifacts in the model would be created.

The result of decimation, retopologization and texture baking is the rendered model (3).

E. CREATING A CHARACTER FOR THE PRESENTATION OF A TEXTILE OBJECT

Textile collectibles were usually made to order for specific people. In order to present a digital clothing model, we must also create a digital character model with the appropriate dimensions and proportions.

FIGURE 7. Clothing and character model imported together in blender before fitting.

Create an initial character model - we first create an initial approximate character model and import it into the scene in Blender along with the clothing model. The MakeHuman tool allows selecting character parameters such as gender, age, muscle volume, overweight, etc. If the default assets offered by MakeHuman are too limiting (e.g., haircut, skin material), community-created assets can be explored and added to MakeHuman.

Adjust the character model - we usually do not know the exact body measurements of historical persons. Therefore, we can only design the character model to fit the clothing model with minimal strain, which is the opposite of designing the original clothing for its wearer. The character model is scaled, and the proportions are adjusted in MakeHuman. Then, the match with the clothing model is verified in Blender.

F. CONTROL SKELETON

A control skeleton needs to be created to control a character's movement. Though we created an initial skeleton in MakeHuman, a much better skeleton with animations can be created in Mixamo. There are two approaches to binding animations with a skeleton: in-place and root motion.

In in-place animation, the character performs the animations in one place, and the motion is made by a programmer in the application code. However, the in-place animation needs to be synchronized with the motion in the application. Otherwise, for example, the feet would slide on the floor when walking.

In the root motion animation, the character's movement in the animation is directly converted to movement in the virtual environment. Therefore, this method is more precise during playback and was chosen in our case. However, the skeleton needs to be modified to include the so-called root bone, a special bone at the very beginning of the skeletal hierarchy used to calculate the motion applied to the character.

Mixamo guides us through setting up the character to create a skeleton for it. It is necessary to place points on the chin, crotch, wrists, elbows, and knees of the character. Mixamo will take care of the rest. An example of the skeleton created is shown in Fig. 8.

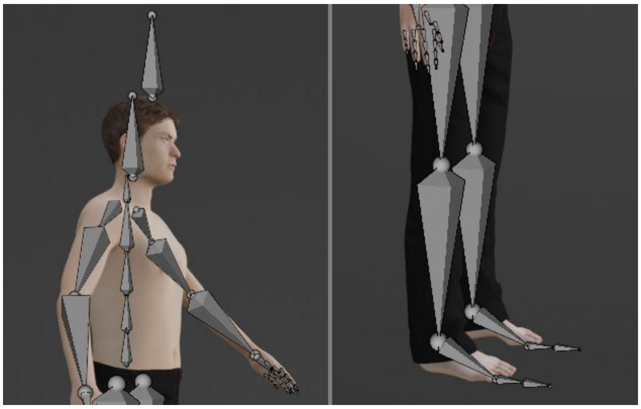

FIGURE 8. Skeleton created in Mixamo.

G. FITTING THE CLOTHING TO THE CHARACTER

A decimated clothing model must be precisely fitted to a character model in the base position by the physical simulation. Currently, the Marvelous Designer software provides the highest quality physical simulation of textile object models. This tool is primarily used to create clothing from scratch. However, it also allows importing an existing clothing model and configuring and simulating it using a subset of the available functions.

Marvelous Designer fits the clothing to the character mostly automatically. However, we may need to pull the clothing in a few points to improve fitting manually. An example of the result of fitting in Marvelous Designer is shown in Fig. 9.

FIGURE 9. Result of fitting in marvelous designer.

If the garment contains rigid parts, these may collapse undesirably during simulation. One solution is to pin some parts of the garment in their position to maintain their shape, using the Pin function in the 3D Garment menu, as illustrated in Fig.10.

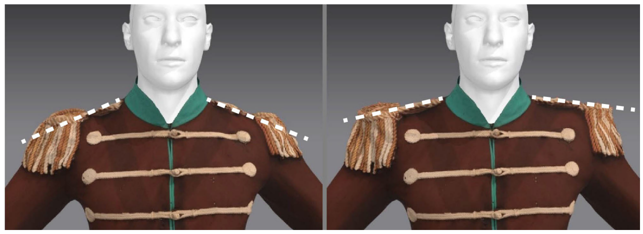

FIGURE 10. Correcting the rigid garment part collapsing at the shoulders using the pin function.

H. CHARACTER RENDERING AND PROXY MESH

Skinning - the determination of how the character's skin deforms in response to the movement of its control skeleton is the skinning process. This is done by assigning a weight to each vertex for a particular bone, determining how much that vertex moves with that bone. One vertex may have several weights for different bones. As many as four bones may affect moving one vertex in real scenarios. The Mixamo tool can set the weights for each vertex automatically.

Weight transfer and blur - we can transfer these weights from the character's skin to the clothing in Blender using algorithms utilizing mapping between the closest vertices. Sometimes after the transfer, the weight map will have jagged transitions that should be blurred, or the model will not deform well.

Insert collision geometry - it is necessary to prevent the character's skin from penetrating through the clothing in an arbitrary pose. This is particularly difficult when the fabric has no fixed motion path and can move freely in different ways depending on external forces. One solution is to add hidden collision geometry. Typically, tapered capsules are tied to specific bones of the character's skeleton as shown in Fig. 11.

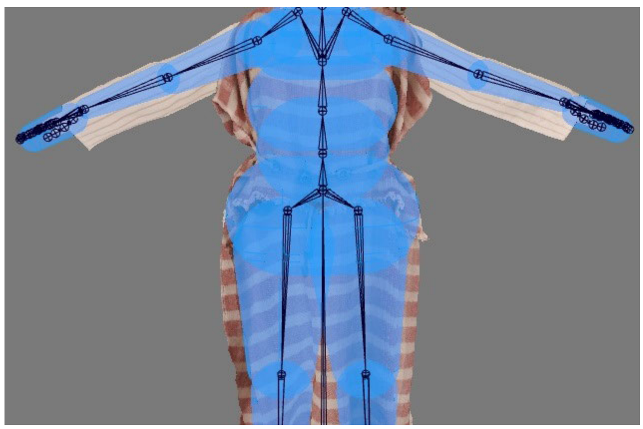

FIGURE 11. Inserting collision geometry between character and clothing models.

Define hidden parts - additionally, it is advisable to divide the skin into groups and not draw the groups hidden under the clothing. The torso can typically be hidden. This also reduces the number of rendered polygons, consequently reducing the necessary computational power. Similarly, in the case of multiple layers of clothing on each other, we can simulate only the visible parts of the inner layers. In Unreal Engine, vertex groups are distinguished based on materials. A single model can have a range of materials for different parts (groups). When the material for a group is disabled, the group is not rendered.

Proxy mesh - some simulation factors, such as clothing colliding with itself, are highly computationally intensive. In order to perform real-time calculations at a reasonable frame rate, a proxy model (4) of the clothing with fewer triangles needs to be created, see Fig. 12. The physical simulation is computed on this simpler proxy model, but the original, more detailed model (before creating the proxy model) is rendered in the application.

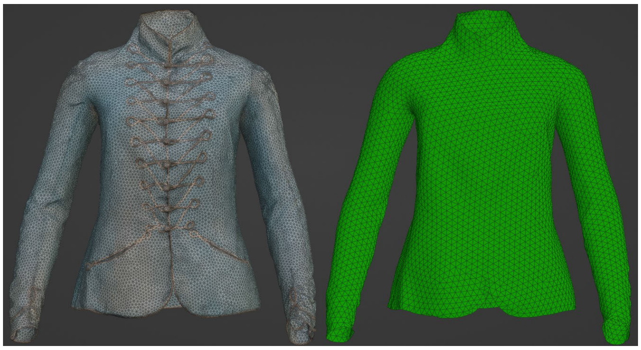

FIGURE 12. The model and its proxy mesh for motion simulation.

The Instant Meshes software, which focuses on retopologizing algorithms, has proven useful for decimating and retopologizing into a uniform structure of equally sized triangles, which is essential for high-quality simulation.

I. ANIMATION AND SIMULATION

For the actual simulation of the clothing model in motion, we used the Unreal Engine 5 environment.

Animations - we aimed to present the collectibles in motion as realistically as possible. Therefore, we used ready-made animations from Mixamo, whose movements were obtained based on motion capture. We exported animations from Mixamo to the Unreal Engine as positions of the character's joints for each frame. The user can choose an animation, such as walking or dancing. However, the animation and the physical simulations are real-time and can be controlled by the user, as is common in computer games.

Masking moving parts - as the physical simulation of clothing movement is computing-intensive, another simplification is desirable. We only perform physical simulation on clothing parts that can move freely on the character. For that, a Max Distance mask can be used to determine how far a given vertex in the model can move from its base position during simulation. The mask effectively determines which vertices are physically simulated and which move with the character using the skeleton. The mask can be created with the Cloth Paint tool. Typically, tight sleeves have a value of 0, i.e. they only move with the character. Loose clothing parts can have a value of, e.g. 70 cm. An example of a Max Distance mask is shown in Fig.13. The maximum possible distance from the base position increases from black to white.

FIGURE 13. Choosing the physically simulated parts of the clothing and the possible movement from the base position using the max distance mask.

Fabric properties - the Unreal Engine allows the setting of parameters to reflect the fabric properties. For example, the fabric stiffness and stretching, how it collides with the environment, how it interacts with the wind, etc. We already set the fabric type in Marvelous Designer, which was used to fit the fabric to the character in the base position. Unfortunately, these fabric parameters cannot be transferred to the Unreal Engine, and the two sets of parameters are different. However, we can use the visual appearance of fabric movements in Marvelous Designer as guidance to set the fabric parameters in the Unreal Engine. If one clothing piece consists of several materials, a mask can be used to assign different fabric properties to different parts of the proxy model.

Computational model The configuration data also includes parameters of the simulation's computational model. A single simulation step can be spread over multiple iterations. In each iteration, the positions of the model particles are integrated based on their previous positions, velocity, and external accelerations. With fewer iterations, the fabric may appear more elastic, and collisions may not be correctly detected, typically in cases where clothing particles are moving too fast. In specific instances where some applied constraints contradict each other, particle flutter may occur.

TABLE 2. Photography parameters for the five selected clothing items (* Note: + 25 detailed handheld photographs).

	Photographs	Rounds (inferior / superior / horizontal)	Max. triangles of Reality Capture model	Exported triangles	Exported textures	Texture utilization	Inferior 1 angle	Inferior 2 angle	Superior angle
Celt - top and skirt	180	2x / 1x / 2x	14,1M	1M	3x 8K	49%	56°	35°	-32°
Celt - two layers and belt	205	2x / 1x / 2x *	50,0M	1M	4x 8K	49%	56°	35°	-32°
Celt - full	180	2x / 1x / 2x	21,6M	1M	3x 8K	60%	55°	35°	-32°
Uniform 1 (No. H20088)	144	2x / 1x / 1x	8,4M	1M	2x 8K	41%	44°	26°	-35°
Uniform 2 (No. H19427)	144	2x / 1x / 1x	11M	1M	2x 8K	44%	45°	27°	-34°
Porter - coat	144	2x / 1x / 1x	11,5M	1M	7x 4K	65%	47°	31°	-33°
Porter - vest	108	1x / 1x / 1x	5,6M	1M	1x 8K	54%	32°	-	-30°
Porter - sash	180	2x / 1x / 2x	8,9M	1M	2x 8K	36%	20°	30°	-31°
Dress (No. H54988)	180	2x / 1x / 2x	17,6M	1M	3x 8K	46%	45°	31°	-33°

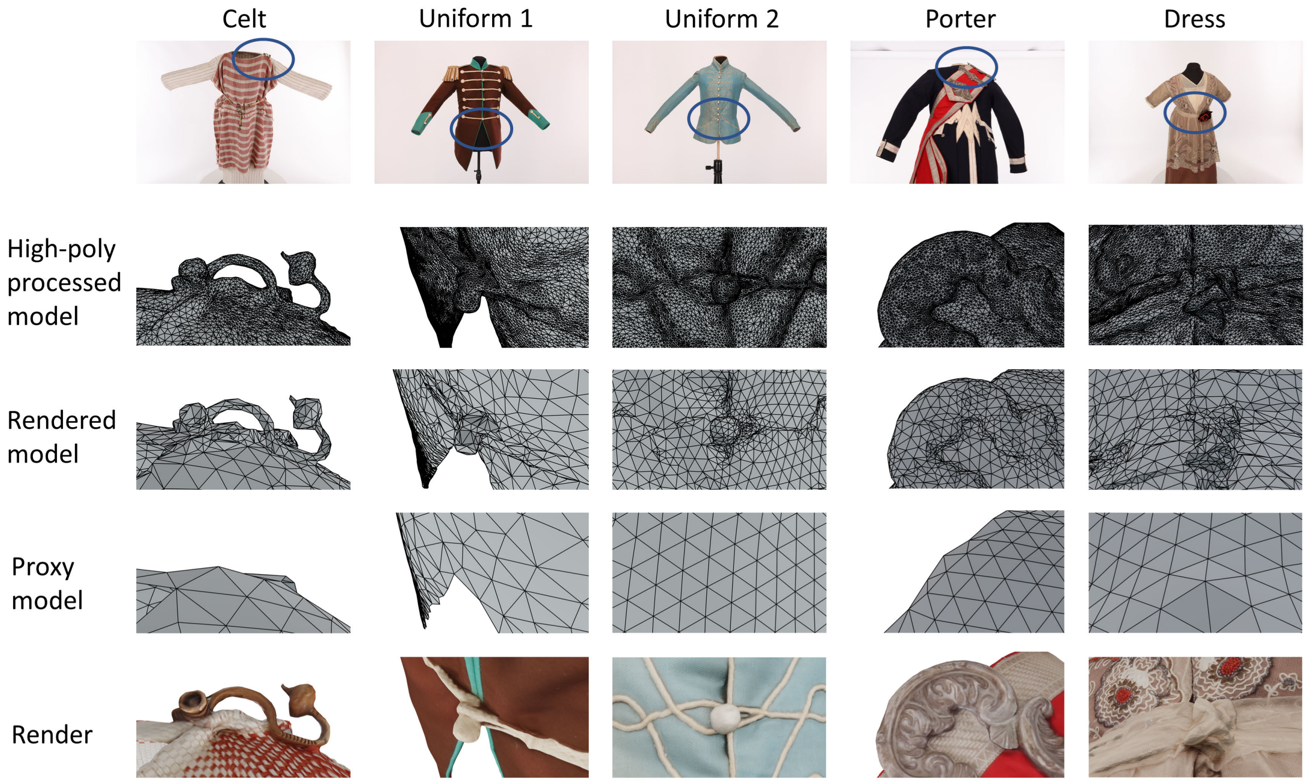

FIGURE 14. Development of models for example clothing objects.

VI. RESULTS

We developed an application for the Unreal Engine environment to test the motion simulation of 3D clothing models processed in the described workflow.

Table 2 summarizes how photographs of the five selected clothing items were taken to create the initial photogrammetric 3D models. Two items included three layers and were photographed three times with different numbers of layers. Depending on the item's complexity, between 100 and 200 photographs were taken in 4 to 5 rounds at different heights and angles. Table 2 also indicates the maximum number of triangles of the model that the Reality Capture software could generate. However, we have chosen to export each model at a resolution of 1 million triangles as a photogrammetric model for further processing. Depending on the complexity of the object, up to eight 8K (8192 × 8192 pixels) texture files are exported for its model.

The number of triangles of the five models created for each clothing item (the outermost model for multi-layer items) during the workflow is given in Table 3.

The development of models for selected clothing objects is shown in Fig. 14. Selected details of objects in the areas marked in the photographs are further represented as polygon networks in three models created within the workflow - the photogrammetric model, the rendered model and the proxy model. Finally, the model's rendering with the corresponding part's texture is shown.

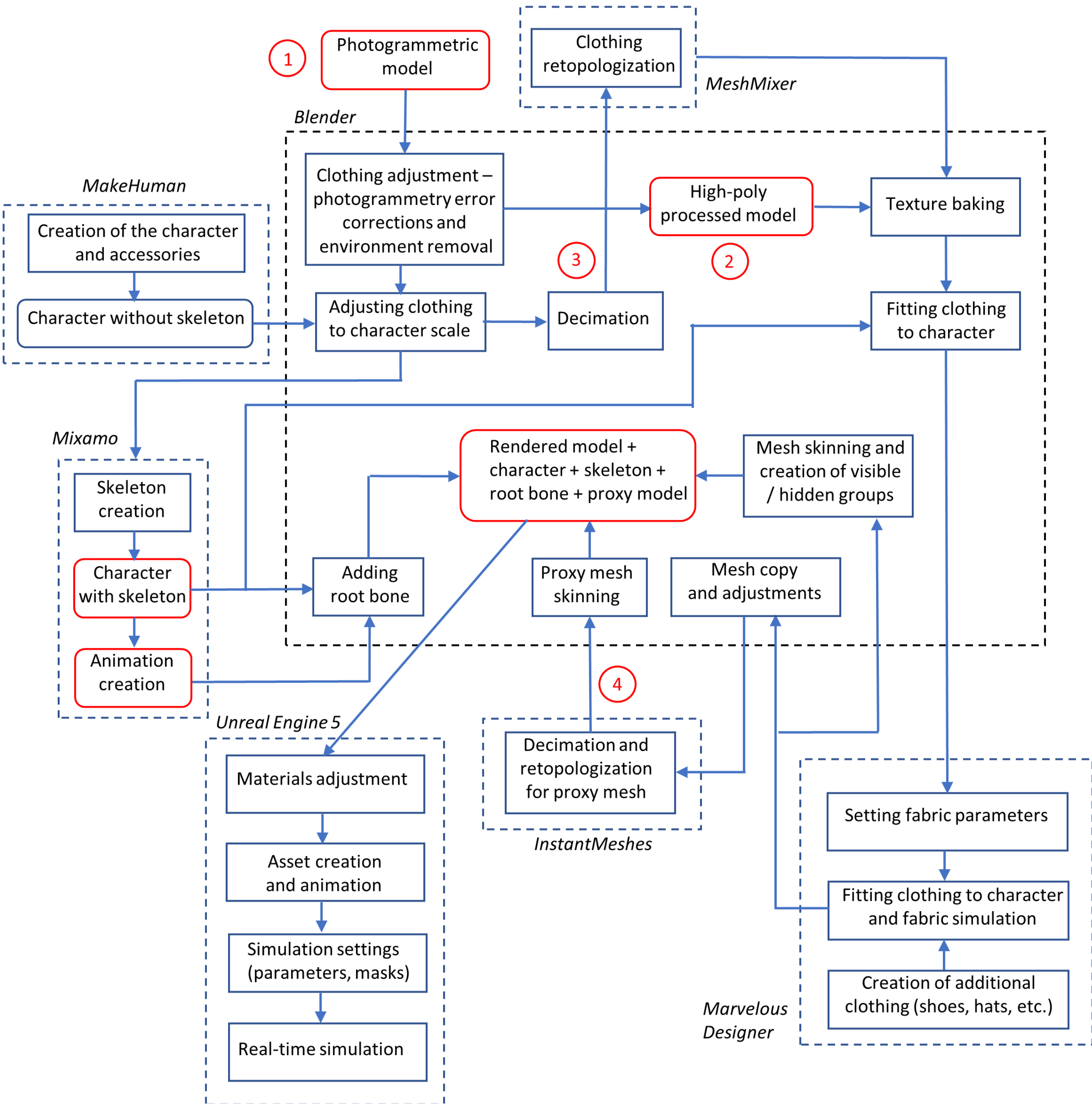

FIGURE 15. **Detailed workflow task relations.**

Recordings of real-time simulations from the application can be found online.[7]

VII. DISCUSSION

Multi-layered clothing, such as underwear and a skirt, or a vest and a jacket, as well as accessories worn over clothes, require a specific procedure. We photographed them on the mannequin, starting from the inner layer and adding more layers. Care must be taken to ensure that the layers are photographed in as consistent a position as possible. This will make it easier to fit the digital models on top of each other. When processing the model of the outer layer, we cut away what can be seen from the inner layers. Marvelous Designer allows importing the layers separately and defining the layer order, which is then respected during simulation. When preparing a simulation in Unreal Engine 5, we divide the mesh into groups and do not draw groups that are not visible. We apply this procedure not only to parts of the character but also to parts of the inner layers of the clothing.

The animation of the character's movement looks less realistic than the animations used in movies. Although animations used were originally obtained using motion

[7] https://models.cesnet.cz/en/wardrobe.html

TABLE 3. The number of triangles of the four models created for each clothing item.

Model	Celt	Uniform 1	Uniform 2	Porter	Dress
Photogrammetry	996398	1000016	999706	999586	1000098
High-poly	788917	851215	836659	568031	962387
Rendered	78124	47037	68090	53026	63427
Proxy	10262	6062	11760	4495	7711

capture, this data typically needs to be further processed in the workflow, such as adjusting the character proportions to the clothing, which can affect the character animation quality. Clothing may also have various accessories that would affect the motion, but were not present during motion capture. Mixamo also uses a simplified version of the skeleton. The spine consists of only five segments, the character has no bones in the toes, no auxiliary bones for facial expressions, etc. Compared to animations in movies, containing up to 65 bones, this makes it difficult to express some movements in sufficient detail. However, this does not have a significant effect on the simulation of clothing movement and its presentation. An important difference from movies is that real-time simulation is required in our target applications.

Overall, the workflow is quite complex, it is well applicable to individual exhibitions, but it is probably not scalable for digitizing large collections of clothing. Some steps can be simplified in the future. The following are some ideas for future improvements.

Editing the photogrammetric model, i.e. removing the environment and correcting errors, can be laborious. For cutting out holes in clothing (e.g., at the end of sleeves), a tool in the form of an add-on in Blender would be useful. For example, the user could click along the perimeter and form a line on the geometry along which the model would split in two. The part forming the fill could then be easily removed. To fill in the holes in the mesh created by photogrammetry, a patch creation tool would be useful, a feature that Blender notably lacks. Blender offers two basic functions for filling holes. The first is a ''grid fill'', which requires a specific structure of the hole to be filled and often produces very strange patches with chaotic topology. The second is the classic ''fill'' which just creates a new area. This patch can be divided into triangles using triangulation, but no new vertices are created, and smoothing to the correct shape is sometimes necessary for larger holes.

Texture baking initially required hours to create UV maps that do not overlap, but after some practice, it took about ten minutes. One could still consider automating the texture baking in ''one click'', which would theoretically be possible with another add-on to Blender.

Accessories in MakeHuman often do not fit the character exactly, and a very limited number of them exist. Ideally, a library of haircuts and shoes would be useful, with configurable materials (unlike MakeHuman).

VIII. CONCLUSION

We have described a workflow for creating 3D models of historical clothing. The models are suitable for highly realistic clothing simulations in a variety of applications. In contrast to clothing simulations currently created for movies, the proposed workflow allows for real-time simulations. Applications include a virtual wardrobe for presenting museum collections in a realistic environment or game animations with real historical clothing. Digital replicas can also create unique documentation of precious collections of historical clothing in museums. In future work, we will explore the possibility of automating some workflow steps to make it

APPENDIX
WORKFLOW TASK RELATIONS

See Fig. 15.

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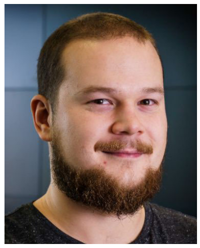

JIŘÍ KUBIŠTA received the M.Sc. degree from the Faculty of Information Technologies, Czech Technical University in Prague. He is currently with the Research and Development Department, CESNET. His research interests include photogrammetry, 3-D modeling, and presentation technologies.

OLDŘICH LINHART received the M.Sc. degree from the Faculty of Electrical Engineering, Czech Technical University in Prague. He is currently with the Research and Development Department, CESNET. His research interests include 3-D modeling, 3-D animation, and graphics programming.

DAVID SEDLÁČEK received the master's and Ph.D. degrees in computer graphics and 3-D reconstruction from Czech Technical University in Prague. He is currently with Czech Technical University in Prague as a Researcher and an Assistant Professor. His research interests include XR technologies and their use for teaching, training, and therapy.

SVEN UBIK (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in computer science from Czech Technical University in Prague, in 1990 and 1998, respectively. He is currently with the Research and Development Department, CESNET, leading a research group on technologies for network applications. His research interests include low-latency video transmissions, programmable hardware, digital cultural heritage, and connecting the world of computer networks with other fields.