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APPLIED RESEARCH

Presentation of Historical Clothing Digital Replicas in Motion

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ABSTRACT The presentation of clothing collection objects in museums brings specific constraints and requirements. Textile objects are particularly sensitive to mechanical handling and prolonged exposure to light. At the same time, it is interesting to see these objects in motion as they were worn. In this paper, we propose a new method of presenting digital 3D models of clothing collection objects that allows us to display these objects in motion. The presentation is handled by two real-time applications. Virtual Wardrobe, designed especially for enthusiasts, aims at simulating the movement of the fabric as closely as possible, with the possibility of zooming in on details and showing clothing in a historicizing environment. Virtual Mirror, aimed towards the general public, allows visitors to virtually put on selected collection objects. The Virtual Mirror can display up to three visitors simultaneously and performs semi-automatic calibration to their character types. The main innovation of the proposed presentation of historical clothing objects is presentation of their detailed 3D reconstruction in motion in real time on dimensionally appropriate models of figures. This makes the solution different from the optimized models used in computer games and the non-real-time rendering used in the film industry. Both applications were subjected to a long-term usage study and a questionnaire study to determine visitor acceptance, which was positive. We summarize the experience of deploying both applications in practice at the museum exhibition.

INDEX TERMS Cultural heritage, museum, garments, fabrics, physical simulation, virtual mirror, virtual try-on, augmented reality, mixed reality, 3D modeling, interactive exhibit, depth camera, long-term study, questionnaire survey.

I. INTRODUCTION

Presenting historical clothing in a museum or exhibition is always a difficult task. The authors of an exhibition have to take into account several aspects. On the one hand, the care of the historical object is important. Considering the age of the garment, there may be a need to treat it gently or to adjust its environment and the way it is presented. On the other hand, museum visitors expect the exhibition to be interesting for them both in terms of content and presentation. These aspects are difficult to fulfill with traditional presentation methods that show garments on mannequins alone.

Traditional approaches to the presentation dilemma focus on the digitization of historical objects and their presentation in a virtual environment. Both steps, digitization and presentation, offer room for improvement. In this article, we focus primarily on the second step – the presentation of historical clothing. Specifically, our overall goal was to complement the digital preservation and presentation of clothing collection objects with dynamic fabric properties.

Although real-time simulation of clothing and the creation of photorealistic 3D assets using photogrammetry are techniques individually used already in video games, the movie industry, and cultural heritage preservation, their combined use poses various challenges, such as optimizing 3D meshes, skinning, and rigging clothing with non-conforming

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dimensions and proportions. The demands of preserving cultural heritage in sufficient detail, including the dynamic behavior of free-form garment objects in motion, bring new challenges to this process that have not been discussed in the literature. We follow up the garment 3D reconstruction workflow summarized in section IV and described in [1] in detail by extending it with a previously undiscussed presentation layer demonstrated by two sample applications for visualizing historical garments.

II. RELATED WORK

The physical display of textile exhibits takes place mainly on mannequins. Alongside other methods, such as stretching the garments with fibers or simply hanging them on a hanger, the use of properly arranged mannequins is the most appropriate (i.e. the most gentle) way of presentation [2]. The mannequins must always be adapted to the specific garments. For smaller sizes, it is necessary to make bespoke mannequins; for larger garments, ordinary ready-made mannequins can be supplemented with pads and padding, for example [3].

During the preparation of exhibitions and displays, a certain contradiction or discussion may arise between the visual aspect of the display (the arranging aspect), where the emphasis is placed on the perfect stretching (stuffing) of the garments, and the aspect of maximum care eliminating the stretching of the garments, which is, of course, at the expense of the appearance and overall effect of the displayed historical garment [4].

In addition to physical displays on site, several museums and institutions present parts of their clothing collections online, mostly using 2D photographs. Among the most well-known museums are *The Metropolitan Museum of Art* [5], *The Victoria and Albert Museum* [6], *The National Museum of American History* [7] or *The Kyoto Costume Institute* [8].

There are also examples of generic web portals. The *Europeana portal* [9] collects records of digitized objects from many European museums and also includes a special section dedicated to fashion objects [10]. All objects are represented by photographs or drawings. *Google Arts and Culture project* contains section *We wear culture* [11], showcasing collections from partner institutions. Here, photographs of clothing items are included in a series of narrative articles. An important part of the sharing portals are also systematic descriptions that adhere to the standards of the technical quality of the photographs and how they were taken (whole, detail), together with systematic descriptions using agreed terminology, see [12].

None of the previous traditional examples, however, focuses on presenting the dynamic properties of textiles in motion. At most, they mediate recorded videos from the original era or newly created videos with physical replicas. Thus, in this article, we will focus on techniques from emerging technologies that allow us to present 3D models of clothes in motion. These are mainly applications in the fields of multimedia, gaming, virtual reality (VR), and augmented reality (AR).

TABLE 1. Methods of creating 3D model of historical clothing according to the original sample and examples of use.

Approach type	Application example
2D to 3D - free inspiration	3D models created according to: - Ancient paintings in China (CLO 3D) [13] - Pictures of riding skirts from literature [14] - Photos of women's folk costumes down to the fabric detail [15]
2D to 3D - accurate reconstruction	3D models created as accurately as possible from surviving technical drawings or physical objects: - Creation of 3D model according to technical drawings of germanic warrior armour [16], [17]. - Creation of 2.5D maps from vectorized decorative motives [18].
2D to 3D - dynamic simulation	Dynamic simulation is used to find: - Costume parameters to fit images of crinoline skirts [19] - Mail armor is created in a relaxed state and dynamically simulated to final pose [20]
Real object digitization	3D reconstruction methods based on photogrammetry and 3D scanning: - Microscopic fabric structure or embroidery details [21] - Puppets scanned with FaroArm, garment parts are recreated from scratch in 3D modeler [22] - Structure light scanner used for digitization of Emir of Bukhara's costume parts alone, on a mannequin, on a person [23]

Although this article focuses on the presentation of a 3D model of a historical garment in motion, it is useful to discuss commonly used methods of obtaining such a 3D model; we specifically use a photogrammetric technique (see Section IV) that produces models with a high number of geometry vertices and preserves accurate surface color information. We have divided the relevant methods for obtaining a 3D model in the field of textile heritage conservation into techniques that use 2D materials as a source (paintings, sketches, individual photographs, blueprints) and those that record a 3D model according to a real object. These can be further subdivided into subgroups; see Table 1.

Free inspiration approaches are based on surviving pictorial records of clothing, such as ancient paintings in China [13], pen drawings in literature [14] or, for example, a small number of contemporary photographs of clothing on people or mannequins [15]. The 3D modeling tool is then used to create a 3D model, respecting these models freely. Some works use standard 3D tools such as Blender or Maya, while others use specialized tools to create clothing patterns and visualize them, like CLO 3D. **Accurate reconstructions**, on the other hand, use original drawings or parts of the surviving garments on which they are based, e.g., war armor [16], [17] or photographs of motifs on textiles [18], where a much smaller degree of creative work is assumed and thus a more faithful reconstruction is produced. The final sub-category, **dynamic simulation**, uses one of the previous methods to create a model in a basic (ideal) pose (without the effects of gravity, relative forces in the fabric, and collision with the body) and then uses physical simulation to create a deformed model resembling the clothing in the final pose - e.g., standing [19] or a warrior walking [20]. It should be noted that the methods are usually combined together with the previous two, and the simulation of the fabric dynamic behavior is already used when the model is created. However, the methods included in this category use physical simulation in order to reveal the actual original state of the historical object.

Digitization of real objects, uses techniques commonly used for cultural heritage preservation [24] in the form of 3D scanning (usually structured light scanner for objects up to human size) or photogrammetry (also called SFM - Structure From Motion) of an existing object. Although these methods assume static objects for recording, they can also be used to reconstruct free-form objects such as clothing under certain circumstances [25]. The variation of applications for textile objects ranges from small objects such as fabric texture and embroidery [21] to medium-sized objects such as clothing accessories [23] or puppets [22], to full-body robes [23]. The resulting 3D models are either displayed in a static form with the possibility of viewing details [23] or are significantly simplified for real-time animation [22]. The following text describes the presentation methods emphasizing motion and is summarized in Table 2.

An interactive tool [26] for studying and presenting specific historical and contemporary weaving techniques allows visualization of the definitions of waves and weaving techniques but is designed for smaller pieces of fabric and does not consider their dynamic properties. The work of Moskvin et al. deals with the faithful reconstruction of crinoline skirts [19], including visualization in dynamic poses. However, these are not animations but final static poses after dynamic simulation (e.g., a woman seated on a horse [14]). This research approach was further applied to the equipment (garment and armor) of a Germanic warrior [16] and also extended with a simulation in a game engine to visualize the dynamics of the mail armor [17]. The reconstruction of the people's costumes in the ancient paintings [13] was carried out in a very similar way. 2D clothing cuts were applied to 3D virtual figures in fabric simulation software (CLO 3D) to create pre-rendered videos for subsequent presentations. Digitization of historical garments using 3D scanners with structured light to create static 3D models for archival purposes was presented in [25].

TABLE 2. **Examples of the presentation of fabrics and clothing in motion in cultural heritage applications.**

Typical method	Application example
Expert tool	- Waves and waving techniques with piece of fabric [26]
Images of static poses after dynamic simulation	- Crinoline skirts [19], riding skirt [14], - Women's folk costumes, created with cloth simulation in Blender [15]
Prerendered videos	- Cloth animation from 3D creation tool like China ancient costumes created in CLO3D [13]
Realtime skeletal animation	- Skeletal animation of avatars in historical clothing, review paper [27] - Example from AR application of Portuguese Malacca heritage building with virtual humans [28] - Moving with puppets in VR [22] - Dynamic characters in AR/VR applications for Cultural Herritage [29]
Dynamic simulation in game engine	- Dynamic simulation of partially rigid objects, ie. rings of mail armour [17]

Some of the works focus on virtual characters (so-called avatars) who complement the presentation of virtual historical monuments. These avatars are not static, they react to the visitor and it is therefore desirable that their clothing is also dynamic. An overview article describing avatars in cultural heritage applications [27] 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 [28].

Virtual mirrors are spatial variants of augmented reality (AR), see [30] and [31]. Basically, it is a display in front of which the users stand, move, and see themselves as in a mirror; thanks to their image captured by a video camera, the user's image is augmented by non-existent (virtual) objects. Although there is a wide range of applications for this concept, from entertainment and gaming through education [32] to personal assistants [33], [34], most applications can be found in fashion. In this domain of fashion, we encounter alternative names such as virtual/AR try-on, virtual fitting room, dressing mirror or costume "try-on" experience.

A virtual mirror is used both for visualization of clothing [35] and for visualization of other elements such as fashion accessories (glasses, handbags and hats, earrings and necklaces), make-up [36], hairstyles [37]. Most of the time, it is a marketing tool to attract customers, where they can try a new feature more easily without having to put in more effort [38]. Due to the larger size, these installations are better suited for stores and their windows, not for home use. There are also works that focus on virtual try-ons in online shopping [39]. Here, the mirror is implemented using a mobile device with a front-facing camera (selfie camera). Due to the limited distance of the user from the device, they are primarily used to change the appearance of the top part of the body (from the chest to the head), ie. make-up try-on [36]. In museum displays, we find the interesting use of a virtual mirror for visualizing the masks of the natives directly on the visitor's face [40]. Although the use of AR in museums is widely discussed [41], the use of magic mirrors to visualize historical clothing is more of a selling point for commercial products such as [42] and [43].

Early implementations of magic mirrors used a half-silvered mirror to combine real-world reflections with virtual objects [33], [34], thus addressing the low resolution of cameras and small display areas. As projectors were also used to achieve large virtual images, these installations were spatially bulky, and the semi-transparent mirrors detracted from the brightness of the virtual image. Recently, large LED televisions and so-called RGBd cameras have been used to realize magic mirrors, which has significantly reduced the space requirements of the installation (e.g. [44]). In addition to the color image, RGBd cameras also record information about the distance of objects in front of the camera (i.e. d-depth). In order to render virtual objects, the positions where they are to be rendered need to be determined. For this, either the so-called AR markers [35], [37] can be used or better, the so-called skeleton or face landmarks of the user are detected and the objects are rendered in reference to it [36], [45], or it is used to deform the 3D model of the augmentation [40], [44]. Recently, with the development of generative adversarial networks (GAN), there has also been an increase in their use. However, there are problems with training the models and also with the speed of response to a change in the user's pose, making these methods more suited for offline processing use [46], [47].

III. RESEARCH AIMS

Our work has two main research objectives. The first objective is to design, develop and evaluate real-time interactive visualization applications that allow the presentation of dynamic properties of objects from clothing collections.

The second objective is to evaluate user feedback on these applications. For this research objective, we set two research questions:

1) How do you like the way clothes are presented (subjectively)?
2) To what extent does the clothing presentation method help you to understand the dynamic properties of clothing? That is, for example, how clothes behave during normal movement, walking or exercise.

We expected the new presentation methods to be at least as enjoyable as the static mannequin presentation method. We also expected the new presentation methods to present the dynamic features better than the static mannequin presentation method.

IV. MATERIALS AND METHODS

Our objective was to design a visualization solution for motion digital models of clothing collection objects. We assume that the digital models were created using photogrammetry with post-processing. The main steps of the model creation workflow can be summarized as follows, more details have been presented in [1].

Creating a 3D model of a textile object that is faithful to the original and allows motion animation requires a specific procedure.

The object is dressed on a mannequin, often custom-made for the object. Typically several hundred photographs are taken to create a base static 3D model using photogrammetry. In our case, we used RealityCapture, but other photogrammetry software can be used. We exported a model of 1 million triangles.

The digital model is then processed by removing the visible parts of the mannequin and other auxiliary objects during photogrammetry. Errors created during photogrammetric processing, such as holes in the mesh or bad mapping in textures, are corrected where appropriate. We use Blender for this purpose.

To reduce the computational complexity of rendering, the model is decimated to the size of tens of thousands of triangles. Both photogrammetry and decimation algorithms can produce a topology that is not well suitable for subsequent animation as artifacts may be produced during motion. Therefore, the decimated model is retopologized to consist of uniform, similarly sized triangles as much as possible. We use Meshmixer and Instant Meshes for this purpose. These modifications can also cause texture distortion, which may require creating a new UV map for the model and bake the texture from the original high-quality model.

Next, a character model is created for the clothing model, with the correct proportions, including a control skeleton. For this task, we use MakeHuman and Mixamo. Using the fabric simulation in Marvelous Designer, the clothing is fitted to the basic position on the figure and skinning of the clothing to the control skeleton is done.

To simulate movement, another simplified version of the model is also created consisting of the order of thousands of as similar as possible, equilateral triangles. This version is again created through decimation and retopologization. The motion of the clothes is simulated on this model, but it is not rendered in the application, it only converts its motion to a rendered, higher-quality model.

Mannequins for photographing textile items should ideally adjust the item in a near T-position or at least have the sleeves filled in and not flowing into the toe. The model created from the photogrammetry can then be animated more easily.

For the illumination of textile collection objects, it is generally preferable to use more intense flash light than long-term steady illumination, both in terms of overall light exposure and minimization of thermal radiation. Based on the power of the flashes typically used for photographing objects in repositories (e.g. Broncolor Siros 800), the flash duration and the number of hundreds of photographs, the total light exposure of one object can be estimated at 130 lux hours. This corresponds to approximately 0.1% of the maximum recommended value per year [48].

Considering our project research goals, we decided to divide the solution into two applications

FIGURE 1. Physical simulation of textile movement while dancing.

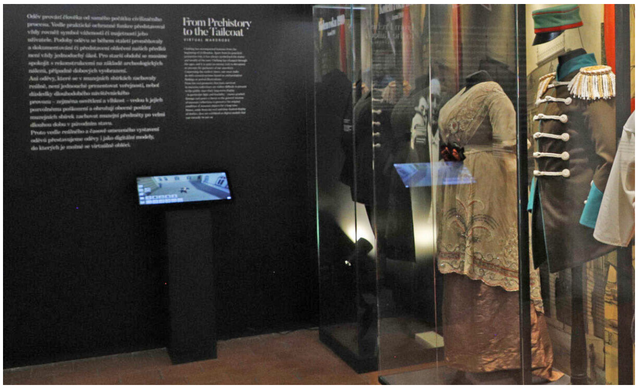

FIGURE 2. Virtual Wardrobe application (left) at the exhibition of historical clothing.

A coat and a hat of a Prague Student Legion member, 1848

In June 1848, street fights broke out in Prague. Commanded by General Windischgrätz, a radical opponent of the social changes, the soldiers aimed to occupy entire Prague and forestall the revolution. They were especially confronted with students who erected barricades in the streets, trying to prevent the army from seizing the city. The students founded an academic (student) legion and wore unified clothes featuring the elements of military uniforms and national costumes, and especially hats that showed their affiliation with various legion groups – cohorts. For instance, philosophy students wore green, law students red, and engineering students blue hats.

FIGURE 3. Virtual Wardrobe user interface. On the left are garment and action buttons, on the right is detailed description of selected item.

- **Virtual Wardrobe** which allows users to view items of the clothing collection with a true-to-life simulation of movement and the ability to zoom in on details and
- **Virtual Mirror** that uses a motion-sensing device to allow people to see themselves wearing a digital copy of a clothing collection item on a large display.

The target visualization differs from tools for presenting static digital models in that it captures the dynamic properties of a textile object through physical simulation. In contrast to simulations used in the film industry, the target applications should work in real-time. Compared to computer games, we use detailed models of real objects. Clothing items can be presented on fitting models of characters in a time period environment and can react to external influences, such as wind.

Digital models of clothing items from the collections of the Prague City Museum and the National Museum in Prague were used to verify the visualizations. Both applications were used at the public museum exhibition of historical clothing items. Feedback from users was obtained both by automatic monitoring of usage and from questionnaires that visitors could fill in.

V. VIRTUAL WARDROBE

The Virtual Wardrobe application allows users close inspection of precious textile collection items including their movement without physical handling. Textile items are dressed on virtual characters, corresponding in proportions to the original wearer of the items. Details of the character, such as the hairstyle and the surrounding scene, combine to form a period-coherent whole. The virtual camera can follow the character from all angles and distances of view. An example visualization with physical simulation of textile movement is shown in Fig. 1.

A. USER INTERFACE

The application was designed to be used in a digital kiosk. The appearance of the digital kiosk at the exhibition is shown in Fig. 2 together with static mannequins.

The appearance of the application is shown in Fig. 3. It can be fully controlled via a touch screen, or using a standard mouse and keyboard. The user interface allows to select a textile object, an animation, such as walking, running or dancing and external effects, such as wind intensity and direction. Selecting an object automatically selects the corresponding character and the scene. The character moves around the scene followed by the camera. The application monitors user interactions. After a certain amount of inactivity, the scene is reset to the default animation state and camera position.

Graphical elements such as fog and particle systems such as falling leaves or a candle flame were added to make the environment look more attractive.

In addition to displaying objects in a historicizing scene, it is also possible to choose a neutral environment with a choice of lighting or a shadeless display, in which the surface of the model is lit evenly and creates no shadows, allowing viewing of small details.

B. IMPLEMENTATION

The Virtual Wardrobe application was created in the Unreal Engine 5 environment[1] in C++ language and the Blueprint visual scripting system. Real-time textile motion simulation was achieved by optimizing the collision calculation using proxy models, processing textile layers separately, using

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[1] https://www.unrealengine.com/

collision objects with simple geometry, and using masks to limit the range of motion of model points.

Unreal Engine 5[2] was chosen because it currently provides the high-quality rendering of complex scenes with a wide range of special effects. The second reason for its choice was its Chaos physics system,[3] which provides high-quality real-time physical simulations suitable for clothing applications.

The time period scenes in Virtual Wardrobe were created from models obtained from the Megascans collection,[4] from available Unreal Engine asset packs[5] and other external sources.[6] Such models usually contain high-quality 4K textures for color and other elements to enhance the model's visual quality, such as normal maps, metallic maps, roughness maps, ambient occlusion maps, etc. These models typically also include lower levels of detail, which speeds up scene rendering.

Open-source software Blender[7] was used for the processing of 3D models. 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.

C. MOTION SIMULATION

The original digital models included approximately 1 million triangles per clothing item. This size was chosen when exporting the model from the photogrammetry software. During post-processing in Blender, we created two smaller decimated models - the rendered model with 60 to 80 thousand triangles and the proxy model with 5 to 10 thousand triangles. The rendered model is used for visualization while the proxy model is used for physical motion simulation.

The motion simulation of clothing was implemented using the Chaos physics system.[8] The points of the proxy model are connected by springs that have different parameters and exert a force on the points. These forces are used to calculate a resultant that determines how the point should move and thus deform the clothing. One simulation step can be spread over multiple iterations. In each iteration, the position of the particles is integrated depending on their previous position, velocity and external accelerations. With fewer iterations, the fabric may appear more elastic, collisions may be incorrectly detected, or particles may vibrate. A higher number of iterations provides better results, but it is more computationally intensive and the motion may not be smooth. The configuration should be therefore chosen according to the complexity of the particular model. The movement of the points is subject to various constraints, the most important of which are of two types.

FIGURE 4. Proxy mesh example with skeleton and human upper body for reference. Proxy mesh parts controlled by skeletal animation are depicted in magenta, the physically simulated parts in the gradients of grey color.

The first constraint is a mask, which for each point determines its maximum distance from its original position given by the character's motion. A non-zero value marks the point as dynamic, meaning it takes part in the clothing simulation.

The second type of constraint is collision prevention with other clothing points, the character, or the environment. Two or more such mutually exclusive constraints may act on a given point, for example when a point is pinched between two colliding objects. This can cause the fabric to become unstable and form visual artifacts. For example, part of the clothing can be pulled in a random direction or bounce randomly. In these cases, the collision conditions need to be adjusted by modifying the collision geometry or by modifying other constraints, such as the maximum distance mask. An example of a proxy mesh with parts physically simulated and parts moved by rigging only is shown in Fig. 4

The skeleton of the character was created in Mixamo.[9] The number of bones depends on which parts of the character we want to animate. In our case, we wanted natural movement of the character's clothes in the environment, but we didn't expect significant hand or head movements. For this, one bone for the ankle and one bone that bends all the toes of the foot at once is sufficient. In total, the skeleton consists of 65 bones.

D. MULTI-LAYER CLOTHING

Clothing collection items often consist of several parts. These can be separate, such as trousers and shoes. Or they can be

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[2] https://www.unrealengine.com/en-US/unreal-engine-5

[3] https://docs.unrealengine.com/5.0/en-US/physics-in-unreal-engine/

[4] https://quixel.com/megascans

[5] https://www.unrealengine.com/marketplace/en-US/store

[6] https://sketchfab.com, https://www.turbosquid.com

[7] http://www.blender.org

[8] https://docs.unrealengine.com/5.3/en-US/clothing-tool-in-unreal-engine

[9] www.mixamo.com

layered, such as a petticoat under a skirt, a vest under a coat, or even more layers on top of each other. A desired feature of the presentation is the ability to choose which layers to wear. We assume only the natural order of the layers as they were typically dressed. There are two options for how multiple layers can be simulated.

The first option is to merge the models of each layer into a common model in Blender. This has the advantage of making it easier to work in Unreal Engine with one model only. However, merging the models in Blender is laborious and would need to be done for every combination of layers to be presented, and switching layers would be difficult to implement. Calculating the cloth self-collisions would be demanding due to the high number of points in the merged model. In addition, it would be difficult to implement different simulation behaviors for different types of fabric in each layer. This could be addressed to some extent by using masks to mark the visible parts of the different layers, but only for the material parameters supported by the masks in Unreal Engine.

We therefore chose the second option, to import the models of each layer separately into the Unreal Engine. The advantage is a simpler implementation of switching the presented layers and a lower complexity of calculating the fabric self-collisions because the models of each layer have a smaller number of points. It is also easier to implement different simulation behaviors for different types of fabric in the layers. The disadvantage is that Unreal Engine does not calculate collisions between separately imported models. Therefore, it can happen that the bottom layer will leak out through the upper layer. This should be avoided by inserting collision objects between the character model and the layer models. Each layer may have its own collision objects. They are composed of simple shapes such as capsules, spheres, or boxes, which are rigidly connected to the bones of the character. The simplicity of these shapes makes the calculation of collisions with clothing far less computationally intensive than fabric-to-fabric collisions. Fig. 5 shows an example of character collision objects.

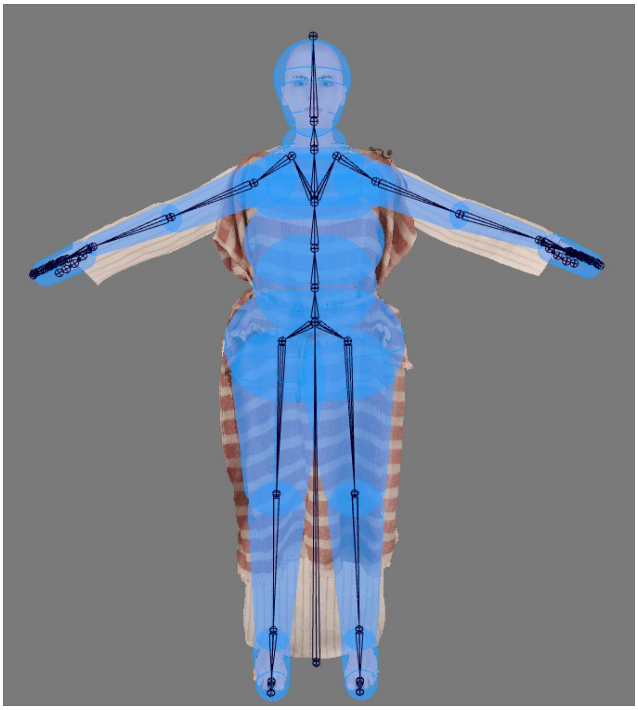

FIGURE 5. Collision objects between the character and a clothing layer.

E. ACCESSORIES

Accessories, such as a handbag or hairstyles made of braided pigtails, should be affected by physics independently of the character itself. These structures have a more rigid shape and it was not appropriate to use clothing simulation for them. Therefore, their animation was solved using so-called rigid bodies with a separate skeleton for each accessory. On the skeleton of the character, a socket can be created for a selected joint to attach the accessory skeleton.

Some accessories, such as a belt, should deform with the character. In that case, the accessory skeleton is created as an extension of the character's skeleton, rather than a separate skeleton connected to a socket.

The accessories have different numbers of bones. For instance, depending on the size of a braid. Long sequences of joints can be difficult to set up correctly, specifying their weight, friction and limiting the joint angles, leading to unstable movements. It is advisable to use as few bones as possible for the accessory to animate realistically. In our case, the belt consists of 8 bones, the bag consists of 19 bones and the braid consists of 9 bones. The computational complexity of multiple bones is negligible in this case.

F. PERFORMANCE

Detection of fabric collisions during its movement and preventing penetration of the character or lower layers through the upper layers is crucial for realistic motion simulation of textile objects. To assess the computational complexity of collision detection and the feasibility of real-time simulation in the Virtual Wardrobe application, we performed a set of computational time measurements. Generated models with specific numbers of vertices were used for the measurements.

Table 3 shows the required simulation time per frame in milliseconds depending on the model size, the number of iterations (as per the Unreal Engine computation) and whether collision detection was enabled. Two fabric layers were simulated, which were imported separately (S) or joined (J). For the separately imported layers, collisions were detected only within each layer. For joined layers, collisions between layers were also detected. The approximate number of vertices per layer is indicated in the model name, for example, 4K means approximately 4000 vertices. The exact number of simulated dynamic particles of both layers together is denoted as DP.

TABLE 3. Simulation times in milliseconds depending on model size, collision detection and the number of iterations.

Model name	Collisions	Iterations		
		5	10	20
S1K / DP 2 029	OFF	0.91	1.41	2.34
	ON	1.58	2.06	3.00
J1K / DP 2 014	OFF	1.24	1.84	3.00
	ON	2.30	3.49	5.30
S4K / DP 8 048	OFF	2.41	3.70	6.05
	ON	5.45	6.55	9.05
J4K / DP 7 998	OFF	3.95	5.98	10.12
	ON	10.95	15.05	25.20
S16K / DP 30 523	OFF	8.45	13.20	22.20
	ON	33.00	38.40	48.20
J16K / DP 30 444	OFF	14.50	22.20	38.00
	ON	101.00	137.00	750+

TABLE 4. Collision detection times in milliseconds and the ratio of collision detection to simulation times.

Model name	Iterations		
	5	10	20
S1K	0.67 (42 %)	0.65 (32 %)	0.66 (22 %)
	1.06 (46 %)	1.65 (47 %)	2.30 (43 %)
S4K	3.04 (55 %)	2.85 (44 %)	3.00 (33 %)
	7.00 (64 %)	9.07 (60 %)	15.08 (60 %)
S16K	24.55 (74 %)	25.20 (66 %)	26.00 (54 %)
	86.50 (86 %)	114.80 (84 %)	—

Table 4 shows the time to compute the collisions only and the ratio of this time to the total simulation time.

The values were measured when the character was at rest, the simulation time typically increases when the figure moves. The Subdivision Count parameter was set to 1 and the Self Collision Thickness was set to 1.

The computer used the following configuration: CPU AMD Ryzen 9 5900HX, 8 Cores, 16 Threads, 32 GB DDR4, GPU NVIDIA GeForce RTX 3080 Laptop, Windows 11 Home and Unreal Engine 5.1.1.

In the J16K model, where 30 444 points were simulated, the calculation did not stop when counting collisions after 20 iterations.

For a smooth movement of the model, it is desirable to achieve a frame rate of 50 or 60 frames per second, that is the frame simulation time should be less than 20 or 16 ms, respectively. With a low number of iterations and subdivisions, collision detection failures are more likely to occur. For example, the sleeve penetrates the collision capsule of the arm and hangs outside the character's arm.

From Table 3 we can see that for smooth motion simulation, it is desirable to use a proxy mesh (i.e. 1K model version), which reduces the simulation size, and to solve the collisions of each layer separately by inserting simple collision objects. From Table 4 we see that the collision detection requires an increasing fraction of the simulation time as the number of vertices increases.

VI. VIRTUAL MIRROR

The virtual mirror allows the museum visitors to try on clothes directly themselves by looking at a large-format color screen, in which they see their image augmented by a historical clothing model. The visitor can change the specific model of clothing on a touch screen located against the wall of the room.

FIGURE 6. Virtually dressed visitors. Visitors move freely in front of the mirror and the virtual outfit adapts to their pose in real time.

FIGURE 7. Room with virtual mirror. See the TV on the left side, the kiosk (tablet) on the right, and footsteps on the floor indicating the calibration zone.

A. ROOM ZONES

The virtual mirror is placed as a separate exhibit in a room with one entrance, see Fig. 7. Upon entering the room, the visitor is automatically dressed in a randomly selected piece of clothing from the available options. The room is virtually divided into zones (see Fig. 8), and the logic of the application's behavior is driven according to the visitor's movement around the room. In the **entrance zone**, new visitors are detected, and a temporary virtual representation of the person is created for them (estimation of the animation skeleton and random assignment of clothes, see Section VI-B). The visitors are moving in this space slightly bent; thus, there are slight deviations in the estimation of their size. Next, the visitors move to the **inner zone** of the room. They can already be seen partially in the mirror, and their visualization is thus displayed. If visitors are in the **active zone**, they are fully visible in the mirror. In the active zone, human footprints are drawn on the floor; most visitors focus on them after entering the room and head towards them.

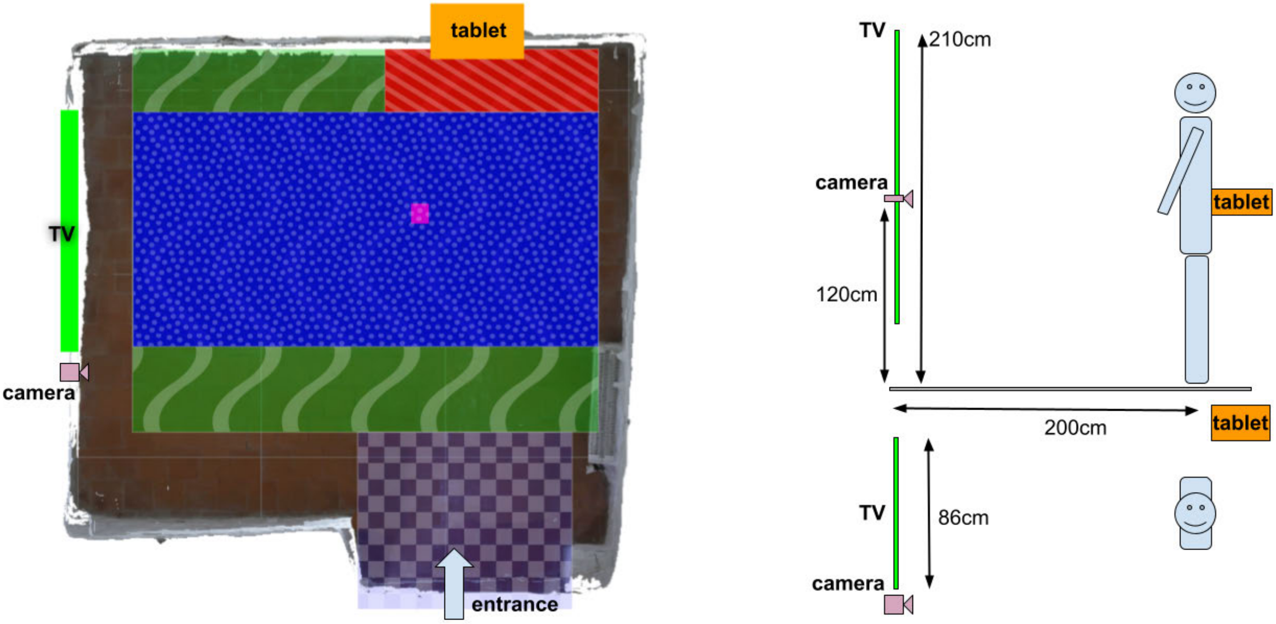

FIGURE 8. Diagram of a room with a virtual mirror. Left: zones distribution in the room: entrance (purple chessboard), inner (green waves), active (dotted blue), tablet (red stripes), and small calibration zone inside active (magenta). Right: representation of the relative position of the camera, TV, user position, and kiosk (tablet) from side and from top.

There is a **calibration zone** around footprints. If the visitor stands still for about 2 seconds in the calibration zone, the virtual mirror system will re-estimate the visitor's skeleton and size - at this point, the model's visualization will change slightly as the virtual skeleton gets closer to the real figure. This calibration adjustment step is performed only once for each visitor. The visitor standing at the **tablet zone** (the orange block in the picture indicates tablet) changes clothes primarily to the person near the calibration zone but can also switch the active person to another person in the active zone. If there is only one visitor in the room standing at the tablet, he/she automatically changes clothes only for him/herself. The room with the mirror can comfortably accommodate three people. The system discards the virtual representations of the persons about 15 seconds after they leave the room through the entrance zone.

B. MODEL ADAPTATION TO THE USER

The room is captured by a single Azure Kinect DK depth camera, whose software automatically recognizes human figures, assigns them a unique identifier (ID), and estimates their skeleton, see Section VI-E for technical details. The skeleton used to animate the model (see Section V-C) does not match the number of bones and their length to the skeleton provided by the Azure Kinect Body Tracking SDK (32 joints). At the same time, the size of the detected body is different from the original model - we have to size the clothing model to the character. Therefore, we implemented a custom version of the algorithm for solving inverse kinematics (FABRIK without constraints, [49]), which allows us to do both retargeting due to the size of the model and due to the different skeleton. The adaptation of the mapping of these parameters is done when the user enters the room and when standing in the calibration zone.

Related work on human body measurements and body type estimation usually focuses on analyzing the RGB image from which they estimate basic parameters such as body height, hip and waist height [50], or even general body shape divided into several categories like triangle, inverted triangle, rectangle, hourglass, or diamond [51]. Instead of analyzing the RGB image, we chose to use the directly detected skeleton, from which we can calculate the head height, hip height, and shoulder height. According to these parameters, we then rescale the reference skeleton on which the given piece of clothing is mapped. While the scaling of the skeleton height results in a simultaneous scaling of the garment (on children the garment is naturally scaled down), the scaling of the hip and shoulder heights results in a disproportionate stretching of the legs and midsection relative to the height. Thus, although there is a deformation of the clothing model, the visual appearance is better than if the model is not adjusted, resulting in intersecting geometry during motion animation.

C. VISUALIZATION VARIANTS

We implemented two different methods of user visualization in front of the mirror. The first uses a 3D point-cloud reconstructed from a depth camera; see Fig. 9. The main advantages of this method are the ability to compensate for virtual mirror projection errors caused by the off-center camera placement, as well as better alignment of the 3D clothing model with the user's 3D point-cloud, and the ability to feasibly replace the user's background with any 3D model

FIGURE 9. **Virtually dressed visitors represented as 3D reconstructed point-cloud, the room background is replaced.**

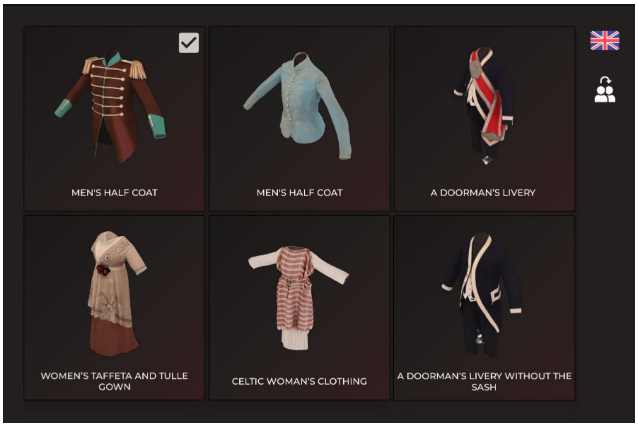

FIGURE 10. **An app for selecting clothes displayed by a virtual mirror.**

of the environment. Disadvantages include low resolution of the point-cloud, missing points due to occlusions by the body itself or due to visitor's clothing made of material unsuitable for the reflection in the IR spectrum, and high levels of depth camera noise manifested mainly in areas of depth discontinuity.

The second method directly displays the RGB image from the camera and extends it with a rendered model of the clothing deformed according to the detected skeleton, see Fig. 6. The main advantage of this method is the use of the full vertical resolution of the RGB camera, where visitors can see themselves in sufficient detail. The disadvantages are the inaccurate alignment of the clothes with the image of the user standing outside the calibration zone and the algorithmically more demanding method of removing and replacing the room background.

After the first 14 days, when variant one was presented at the exhibition, we responded to negative feedback from visitors. They complained about the low resolution of the image (point clouds), especially in the face part. Therefore, after this time, we changed the display method to the second variant, which is already positively received, and visitors are more focused on the presented clothes. All the studies presented in this paper were performed with this second version. Our findings are supported by the work of Cho [52], where she also examined other effects of observed self-image on acceptance of augmentation.

D. USER INTERFACE

Most applications using the Kinect interface for human motion sensing try to use a touchless interface for control (e.g. left/right-hand wave gestures), e.g. [53] and [54]. Unfortunately, these interfaces are often difficult for humans to reproduce without training, and badly performing users evaluate poor system responses as a bug in the overall system. Therefore, we decided to use a more classical approach for the exhibit, using a simplistic touch interface on the accompanying tablet (see room layout in Fig. 7 and touch user interface in Fig. 10). In this way, users can see the specific piece of clothing they choose and can relate it to what they see in the mirror. At the same time, there is direct access to each piece of clothing, eliminating the cumbersome, sequential list scrolling that is necessary when using a touchless interface. Although the virtual mirror allows multiple pieces of clothing to be displayed at once (e.g., a shirt at the same time as a coat), initial experiments have shown that adding and removing layers is difficult for users to understand. Therefore, we limited the control application to simply switching between predefined clothing combinations. Although each user can be assigned a different piece of clothing, see Fig. 6, the application displays the clothing only on the currently selected user (see the red circle in Fig. 6, and check mark next to the half coat in Fig. 10). The application includes an icon to switch the active user located below the icon for application language change.

E. TECHNICAL PARAMETERS

The virtual mirror application was created in the Unity[10] game engine, which is well supported in the camera sensor community. We experimented with two Kinect cameras (Kinect for Windows V2 and Azure Kinect DK). We chose the second one based on preliminary results because of its higher image resolution and more stable recognition of the user's skeleton. The clothing model applied to the user's character matches the description in the Section V-C. The camera image is analyzed using the Kinect Body Tracking SDK[11] to estimate the user's skeleton. The Kinect Body Tracking SDK contains several solvers for image analysis, and we use the CUDA version with support for the ONNX pre-learned deep network model that uses graphics card acceleration.

The Azure Kinect camera specifies each sensor's settings individually[12] (RGB and depth sensors). In our case, the color sensor's resolution and field of view are 3840 × 2160px (16:9) and FOV=$90^\circ \times 59^\circ$. Depth mode is set to a wide angle with a deeper depth range (WFOV Binned preset, FOV=$120^\circ \times 120^\circ$, depth 0.25-2.88m), frame rate 30FPS. Since we use only one fixed camera, we do not use data

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[10] https://unity.com/

[11] https://learn.microsoft.com/azure/kinect-dk/

[12] https://learn.microsoft.com/azure/kinect-dk/hardware-specification

from the IMU unit or external synchronization. The camera must be oriented horizontally due to the skeleton recognition method used. Therefore, we only use a central cutout of 1216 × 2160px (TV aspect ratio 16:9) from the RGB video stream, which is stretched over the entire TV surface. The large format TV screen has a diagonal of 65" (163cm) and a resolution of 3840 × 2160px and is oriented in portrait orientation. Rendering of the final image (i.e. rendering of the clothes + video stream) is done in the native resolution of the TV at 50FPS.

In virtual mirror implementations, the camera is often placed above the display device [44], [54], [55]. We experimented with placing it both above and below the TV and next to the TV and chose to place it in the center of the TV height on the left side. We observed inappropriate image distortion and cropping when placed above/below the TV. For example, a similar placement to the one we chose is used in [53], where the camera is placed in front of the screen. The top edge of the TV above the ground is 210cm, the camera placement is at 120cm height, and the recommended distance of the user from the device is approximately 2m (indicated by markers on the ground, see Fig. 7 and Fig. 8).

The clothing selection app (see Section VI-D) is implemented on the Android platform in the native Kotlin language. The tablet with the installed app is placed at an easy-to-reach distance from the calibration zone, see Fig. 7, and resembles a touchscreen kiosk commonly used in museum installations. We communicate with the mirror software wirelessly using a custom protocol based on the REST paradigm. The server is the mirror application, and the client application is the Android application for clothes selection on the kiosk. The mirror application provides the client application with a complete data model (texts, images, lists), so we do not need to update two programs when updating the available clothing.

VII. USER EVALUATION

Main user evaluation was carried out as part of the exhibition called *From Prehistory to the tailcoat*, which was one of the goals of the Virtual Digital Wardrobe project. The exhibition was installed in the Prague City Museum in House at the Golden Ring. The aim of the exhibition was to present visitors with selected restored clothing or replicas of clothing. The exhibition consisted of three parts:

1) static presentation of the clothing on mannequins (see Fig. 2),
2) presentation using the Virtual Wardrobe application (see Fig. 2) and
3) presentation using the Virtual Mirror application (see Fig. 7).

The exhibition opened on April 25, 2023, and a closing date has not yet been set.

This exhibition was used to conduct a quantitative user evaluation of each presentation method using two procedures. First, we conducted anonymized monitoring of user interaction and evaluated objective parameters of interaction with the applications over a 1-month period in the long-term study (see Section VII-A). Next, we conducted a questionnaire survey (see Section VII-B) in which we asked visitors about their subjective evaluation of each presentation method according to research questions introduced in Section III.

```
{
"appName": "Virtual Wardrobe",
"version": "1.0.6",
"date": "2023-06-19T07:09:14.487Z",
"ipAddress": "192.168.1.133",
"flag": "INTERACTION",
"interaction": "wind_on"
}
```

FIGURE 11. **Example record of user interaction with Wind On button.**

A. LONG-TERM STUDY

In the long-term study, we evaluated user interaction with Virtual Wardrobe and Virtual Mirror. We did not evaluated static dress presentation because there was no data collected from this presentation method. In the study, we were interested in how long the users would interact with a given presentation method, whether they would try to change clothing, and whether they would examine the dynamic properties of the clothing.

Data from the long-term study were collected from July 1, 2023 to July 31, 2023 during museum opening hours (Tuesday-Sunday 8:00-20:00). That is 312 hours in total (26 days).

1) COLLECTED DATA

For each presentation method, various types of user interaction events were collected. The data was stored in JSON text format, which is human-readable and easy to process programmatically. An example of a wind activation record in a scene of Virtual Wardrobe application is shown in Fig. 11.

For the Virtual Wardrobe application, 36 types of events were recorded, such as changing models, layers, animations, external effects, or displaying textual information. It is also possible to record camera movements, providing a detailed record of the user's passage through the application. However, these records were not used in this study. To separate individual user sessions without using external resources such as the camera, we used the timeout. After a period of inactivity, set to 60 seconds, we assume that the user has left the application. The application resets to the initial state and then moves to the INACTIVE state. The assignment of previous events to the user is terminated and events are stored. The next time some interaction is initiated, an AWAKE record is created and a new user session is started.

For Virtual Mirror, we used a similar approach. We collected data from both the Virtual Mirror application and from the tablet application. Altogether we collected 22 types of events with parameters. First of all, we recorded events

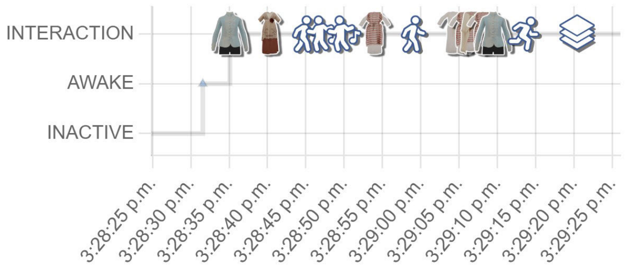


FIGURE 12. **Visualization of the timeline with events recorded from one user session for Virtual Wardrobe application.**

related to person movement, i.e. identification of a new person, calibration of the person in the calibration zone, and tracking person movement between individual zones. Next, we also recorded events related to change of clothes, change of active persons and change of language. Similar to Virtual Wardrobe, we also implemented timeout to define an interaction session, so after 15 seconds of being out of the entrance zone the person session was finished.

2) DATA ANALYSIS

During the long-term study experiment, 478 visitor sessions were started on the Virtual Wardrobe interactive kiosk. Sessions can also be visually displayed on different time scales. An example of zooming to a particular user session is shown in Fig. 12. The icons show which objects in the collection have been displayed, which animations have been selected, and the timeline shows how long the user has spent on each part of the presentation.

Statistical analysis of data showed that for the Virtual Wardrobe application, the median time of the visitor session using the kiosk was 76 seconds. Slightly more than half of visitors (52%) used the layer change feature and slightly less than half of visitors (48%) used the wind effect. The average number of layer changes was eight. Using motion animation was common, with the walk simulation being the most popular (22% visitors) followed by the dance simulation (18% visitors).

For Virtual Mirror we recorded 2997 person sessions. Compared to data from the Virtual Wardrobe application there are 6 times more sessions. The main reason is that Virtual Mirror identifies each individual person in a group, but such a group is probably identified as one session in the Virtual Wardrobe application.

The median time of a person session in Virtual Mirror was 33 seconds. The average number of clothes changes in a person session was 1. However, only in 1357 person sessions (45%) the clothing was changed. In those sessions, the average number of changes was 2.

3) OBSERVATIONS OF USER BEHAVIOR PATTERNS

In addition to statistical analysis, we also analyzed the subset of recorded data for specific user behavior patterns. Therefore, this analysis is not supported by statistical data, but is based on the observation of timelines and videos from sessions. There were several behavior patterns that were observed for Virtual Wardrobe.

- We found two main types of visitors. Visitors in the first group spent longer time (several seconds) looking at individual models and clothes. When they run an animation or when they activate the wind, they observe the model and probably analyze it.
- Other visitors, on the other hand, switched very quickly between models or layers of clothes, which probably did not allow them to view the models in detail. We suspect that these could be children who often come as part of school classroom activities or summer camps.

Analysis of subset of recorded from the Virtual Mirror application revealed following behavior patterns:

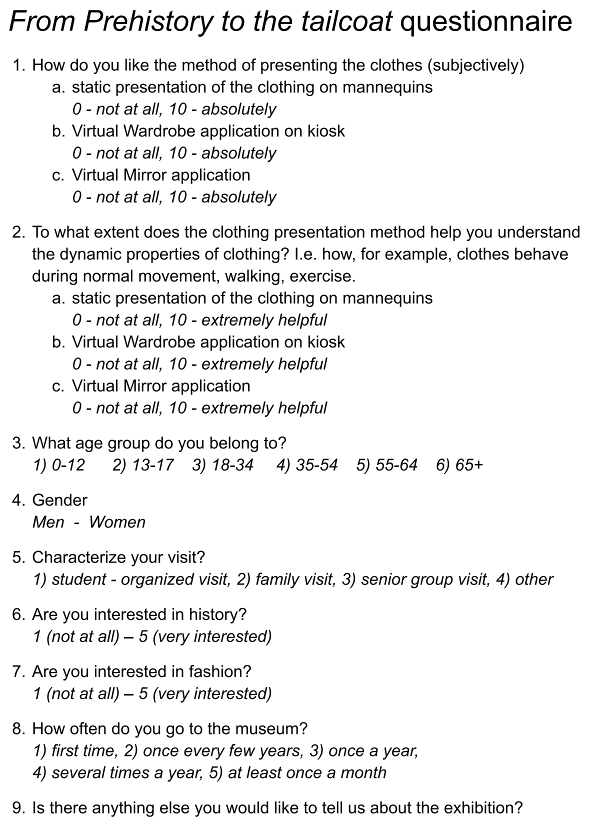
- Visitors enter the room and, thanks to footprints on the floor, they head to the calibration zone, where they stand and observe their image in a relatively static manner.
- More curious visitors try on and change clothes and try slight changes of pose, such as hands on the hips or waving. Then they take a picture with their mobile phone.
- Groups of users behave differently, experimenting, trying on different or the same clothes, and taking a group photo.
- The movements of groups of people are much more dynamic.
- More demanding movements, such as dancing, turning around in front of the camera, etc., are very sporadic.

4) CONCLUSIONS AND PRACTICAL INSIGHTS

Based on the recorded activities, we conclude that the users were interested in both applications, paying attention to them, and experimenting with them. In both applications, we observed several user behavior patterns. There was always a participant group that spent a significant amount of time with the application, suggesting that this participant group may have spent time examining the clothing and its characteristics. And there was also another group of users who used the application more as entertainment without deeper and longer exploration. Both of these groups are target groups for our applications. However, it is worth mentioning that our data do not answer the question of how large these groups are in terms of total museum visitors.

The long-term study also showed us the practical problems associated with the preparation, installation, and operation of digital exhibits in historical museum spaces.

- It is advisable to consult the kiosk architect and agree on suitable cooling vents, which should be periodically cleaned so that the computer does not overheat. This may greatly impact computer speed, leading to poor user experience.
- The viewing angle of the monitor should provide good color rendering for a wide range of visitor heights. It is advisable to check the display parameters in both horizontal and vertical directions.



From Prehistory to the tailcoat questionnaire

1. How do you like the method of presenting the clothes (subjectively)
   a. static presentation of the clothing on mannequins
      0 - not at all, 10 - absolutely
   b. Virtual Wardrobe application on kiosk
      0 - not at all, 10 - absolutely
   c. Virtual Mirror application
      0 - not at all, 10 - absolutely
2. To what extent does the clothing presentation method help you understand the dynamic properties of clothing? I.e. how, for example, clothes behave during normal movement, walking, exercise.
   a. static presentation of the clothing on mannequins
      0 - not at all, 10 - extremely helpful
   b. Virtual Wardrobe application on kiosk
      0 - not at all, 10 - extremely helpful
   c. Virtual Mirror application
      0 - not at all, 10 - extremely helpful
3. What age group do you belong to?
   1) 0-12 2) 13-17 3) 18-34 4) 35-54 5) 55-64 6) 65+
4. Gender
   Men - Women
5. Characterize your visit?
   1) student - organized visit, 2) family visit, 3) senior group visit, 4) other
6. Are you interested in history?
   1 (not at all) – 5 (very interested)
7. Are you interested in fashion?
   1 (not at all) – 5 (very interested)
8. How often do you go to the museum?
   1) first time, 2) once every few years, 3) once a year,
   4) several times a year, 5) at least once a month
9. Is there anything else you would like to tell us about the exhibition?

FIGURE 13. **Questionnaire for the survey at the exhibition. The first two questions are our research questions, and questions 3–8 characterize visitors. The last question asks for additional comments.**

- When using a camera or a depth camera for exhibit, it is necessary to ensure adequate lighting of the premises and use a suitable background.

B. QUESTIONNAIRE SURVEY

The aim of the questionnaire survey was to find out the subjective evaluation of individual clothing presentation methods. The experiment took place during two days on 25 July 2023 (first term) and 1 August 2023 (second term). Visitors were approached after the exhibition and presented with a questionnaire to complete.

1) QUESTIONNAIRE DESIGN

The questionnaire contained 9 questions. The first 2 questions were the research questions of the experiment (see Section III). Remaining 7 questions asked about participant details such as demographic information, gender, relationship to fashion and history and frequency of museum visits. The complete questionnaire with questions and answer choices is shown in Fig. 13. The set of questions was designed based on recommendations from the literature, e.g. [56] with respect to our research questions.

2) COLLECTED DATA

In the first term, 46 responses were received, and in the second term, 50 responses were received, for a total of 96 responses. Of these responses, we had to remove 9 responses as the questionnaire was not completed in full for questions 1 and 2. So **final number of responses was 87**.

TABLE 5. **Result of statistical analysis for Question 1 and Question 2 of the questionnaire. We calculate the mean, median, standard deviation, minimal, and maximal values.**

Q	Static presentation	Virtual Wardrobe	Virtual Mirror
Q1	Mean: 8.21 Median: 8.00 Standard Deviation: 1.75 Minimum Value: 3.00 Maximum Value: 10.00	Mean: 8.45 Median: 9.00 Standard Deviation: 1.70 Minimum Value: 3.00 Maximum Value: 10.00	Mean: 8.15 Median: 9.00 Standard Deviation: 1.88 Minimum Value: 3.00 Maximum Value: 10.00
Q2	Mean: 5.71 Median: 6.00 Standard Deviation: 3.12 Minimum Value: 0.00 Maximum Value: 10.00	Mean: 8.20 Median: 9.00 Standard Deviation: 1.93 Minimum Value: 2.00 Maximum Value: 10.00	Mean: 7.03 Median: 7.00 Standard Deviation: 2.46 Minimum Value: 0.00 Maximum Value: 10.00

The participants in the experiment were **28 men** and **57 women**. In terms of **age groups**, the participants were divided as follows: a) 0-12 years: 14 participants, b) 13-17 years: 12 participants, c) 18-34 years: 10 participants, d) 35-54 years: 34 participants, e) 55-64 years: 13 participants, and f) 65+ years: 4 participants.

In terms of **interest in history**, 55 participants were interested in history, only 11 were not interested in history, and 21 responded neutrally. In terms of **interest in fashion**, 27 participants were interested in fashion, 35 were not interested in fashion and 24 answered neutrally.

3) DATA ANALYSIS

The results of the questionnaires were evaluated in relation to the first two questions which were our research questions. We also analyzed these questions in subgroups based on answers to questions 3-9, i.e. the age of the respondent, the gender of the respondent and his/her interest in history and fashion, and frequency of museum visits.

a: RESULTS FOR QUESTION 1: HOW DO YOU LIKE THE METHOD OF PRESENTING THE CLOTHES (SUBJECTIVELY)?

From the results, it can be observed that the visitors liked all 3 methods, see Fig. 14. Most responses were 6 or more on the Likert scale from 0 (does not like at all) to 10 (absolutely like it).

Statistical analysis is given in Table 5 row Q1 and Fig. 16, with mean values 8.21 (static presentation), 8.45 (Virtual Wardrobe), and 8.15 (Virtual Mirror). These data imply that most users liked the Virtual Wardrobe method, while slightly fewer visitors liked the static presentation and Virtual Mirror. The results for one-way ANOVA are F: 0.691 and p: 0.502. This suggests that the difference in mean values is not statistically significant. In other words, all three methods were rated equally well.

We also calculated differences between user groups based on gender, age, interest in history, interest in fashion, and frequency of museum visits (questions 3-9). We found differences in small number of subgroups. First, in Men/Women subgroup there was difference in the order of methods. For Men it was Virtual Wardrobe (avg. 8.5), Virtual Mirror

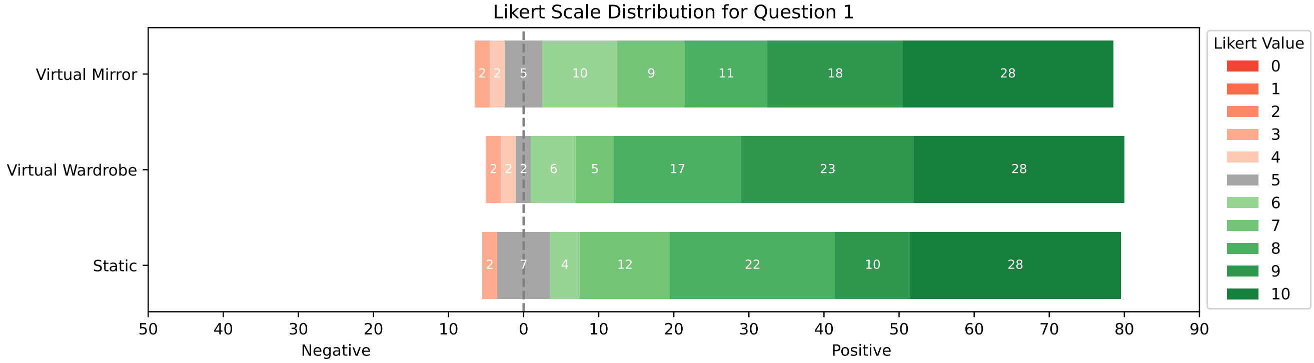


FIGURE 14. **Responses for Question 1 in form of Likert graph.**

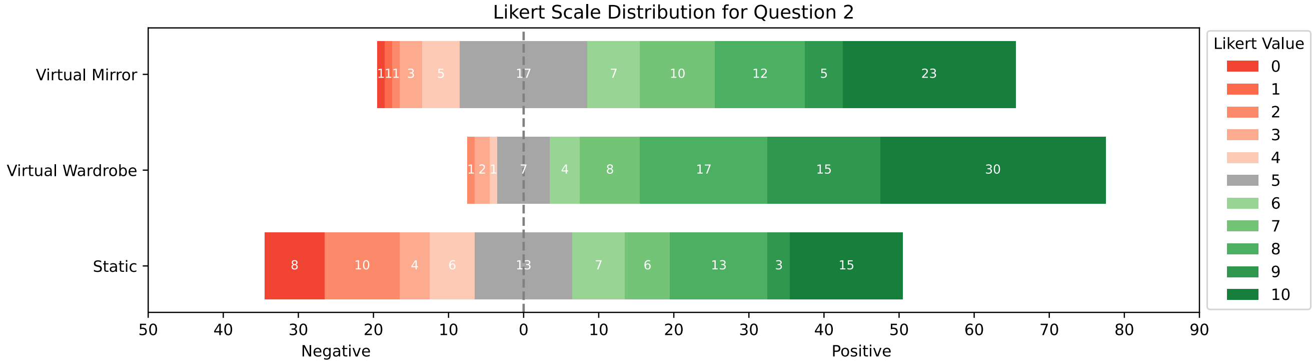


FIGURE 15. **Responses for Question 2 in form of Likert graph.**

(avg. 8.0) and static (avg. 7.5). For Women it was static (avg. 8.5), Virtual Wardrobe (avg. 8.4), and Virtual Mirror (avg. 8.2). Second, there was a significant difference in the preference of methods for age groups 0-12, who preferred Virtual Mirror (avg. 9.5) to Virtual Wardrobe (avg. 8.6) and to static presentation (avg. 6.9).

b: RESULTS FOR QUESTION 2: TO WHAT EXTENT DOES THE CLOTHING PRESENTATION METHOD HELP YOU UNDERSTAND THE DYNAMIC PROPERTIES OF CLOTHING?

For Question 2 it can be observed in graph in Fig. 15 that the participants chose the Virtual Wardrobe method as the best method to understand the dynamic properties, followed by the Virtual Mirror method and finally the static presentation method. Responses were again on the Likert scale from 0 (does not help at all) to 10 (absolutely helpful).

Statistical analysis is given in Table 5 row Q2 and Fig. 17, with mean values 5.71 (static presentation), 8.20 (Virtual Wardrobe) and 7.03 (Virtual Mirror). The results for one-way ANOVA are F: 20.59 and p: $5.06{\cdot}10^{-9}$. This suggests that there are statistically significant differences among the means of the three methods, so it indicates that not all methods have the same mean score. The results of the Tukey HSD test, which provides a pairwise comparison between variants, show that all three variants differ significantly from each other in terms of mean values, with Virtual Wardrobe having the highest mean, followed by Virtual Mirror, and then static presentation.

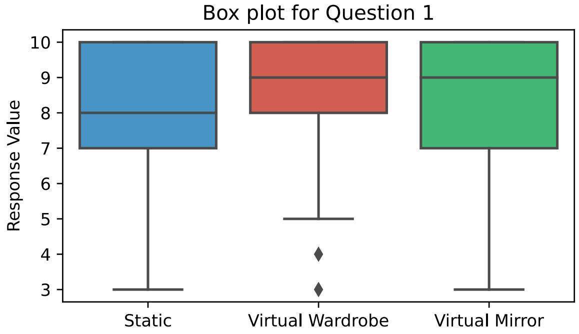


FIGURE 16. **Statistical analysis in form of box plot for Question 1: How do you like this type of clothing presentation?**

We also calculated differences between user groups based on gender, age, interest in history, interest in fashion, and frequency of museum visits (questions 3-9). We found that in all subgroups the results correspond to statistics for the whole sample, some of them also with significant differences between our three presentation methods.

4) DISCUSSION

The statistical results for Q1 confirmed the results of the long-term study that museum visitors liked all the methods

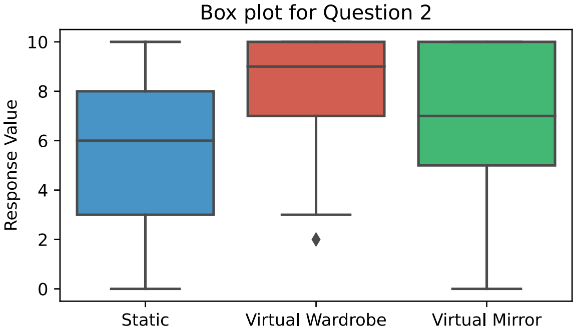


FIGURE 17. Statistical analysis in form of box plot for Question 2: How does this type of presentation help you to understand the dynamic properties of the clothing object?

how clothes were presented to them at the exhibition. Differences in the rankings of each method for subsets of visitors showed that each group may prefer different methods, but the differences were in most cases not significant.

In assessing the extent to which each method helps in understanding the dynamic properties of clothing, museum visitors selected Virtual Wardrobe first, Virtual Mirror second, and static presentation third. This is in line with our expectation that both applications should be better than a static presentation. When comparing the two applications, we assume that Virtual Wardrobe won because of several features. First, the Virtual Wardrobe application has a higher resolution, which allows it to show more detail. Second, the application uses a fixed character model and predefined animations, so it shows smoother animations of clothing, which is also more dynamic. We want to target the dynamics of clothing in the Virtual Mirror application in future work. However, the resolution of the application depends highly on the hardware of the depth camera.

VIII. CONCLUSION

We presented two new methods for visualizing 3D reconstructed models of historical clothing in motion. The target user groups are museums managing textile collections or companies operating in the fashion industry. The Virtual Wardrobe application focuses on the visualization of clothing supported by physical simulation of dynamic fabric properties. The Virtual Mirror application dresses up to 3 museum visitors simultaneously in historical clothing using human skeleton detection with a depth camera.

Long-term studies have shown visitor interest in using both apps and their ability and interest in changing clothes and exploring dynamic properties of clothes. A questionnaire study showed that our methods of presenting the clothing are equally well received by visitors compared to the static display with mannequins. But at the same time, our methods allow visitors to better visualize the clothing behavior in motion than the static display method. The Virtual Wardrobe app performed better in this evaluation than the Virtual Mirror app.

Future work could be focused on optimizing and simplifying the model preparation procedure for motion visualization, which would enable use for a larger set of clothing. We will also focus on improvement of the Virtual Mirror application. First, we want to improve the composition of virtual clothing on the participant. Next, we will add dynamic behavior of the clothing similar to the Virtual Wardrobe application.

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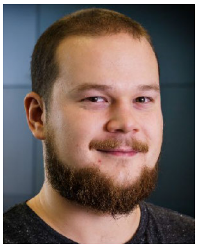

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