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Preliminary communication

Copyright Protection of 3D Digitized Sculptures by Use of Haptic Device for Adding Local-Imperceptible Bumps

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Abstract: This research aims to improve some approaches for protecting digitized 3D models of cultural heritage objects such as the approach shown in the authors' previous research on this topic. This technique can be used to protect works of art such as 3D models of sculptures, pottery, and 3D digital characters for animated film and gaming. It can also be used to preserve architectural heritage. In the research presented here adding protection to the scanned 3D model of the original sculpture was achieved using the digital sculpting technique with a haptic device. The original 3D model and the model with added protection were after that printed at the 3D printer, and then such 3D printed models were scanned. In order to measure the thickness of added protection, the original 3D model and the model with added protection were compared. Also, two scanned models of the printed sculptures were compared to define the amount of added material. The thickness of the added protection is up to 2 mm, whereas the highest difference detected between a matching scan of the original sculpture (or protected 3D model) and a scan of its printed version (or scan of the protected printed version) is about 1 mm.

Keywords: copyright; digitization; haptic device; sculpture; 3D printing; 3D scanning

1 INTRODUCTION

Works of art characterize the creative level of civilization. Sculptures as works of art are created using a specific technique closely related to the era in which they originate [1]. In the authors' previous work [2], a new approach for protecting digitized 3D cultural heritage was created. Namely, a sculpture of a man's head which belongs to the Gallery of Matica Srpska was digitized, and instead of the, until then, dominant ways of protecting such statues, a new one was proposed, which boils down to the addition of noise [3-13]. In cooperation with the sculptor, the zones on the sculpture were defined, to which some material, i.e., clay, was added. Such a sculpture was then scanned, and furthermore, a comparison of that digitized 3D model with the 3D model of the original sculpture was made. Of course, some differences were found in the coordinates of the vertex of the sculpture where the material was added. The model with the added material is called the 3D model with built-in protection. The main idea is to make the model with built-in protection available to the public for free use, whereby every user could enjoy the artistic experience of a given 3D sculpture, without being aware that the 3D model is minimally different from the original 3D sculpture. Authors' assumption, that the difference is visually difficult to see, was confirmed by a survey conducted on 195 respondents [2]. As a continuation of that research, the present idea is to perform the digital sculpting and shielding procedure using a haptic device. During sculpting with a haptic device, there is physical resistance inside the device that gives us a more realistic impression during digital sculpting. This kind of sculpting is much more reminiscent of traditional hand sculpting because there is physical resistance in contact with the digital model. The combination of two techniques such as 3D scanning and digital sculpting is a good way for a visualizer or artist to use it for 3D reconstruction [14].

The aim of this research is to add protection (masses) to a 3D virtual model with the use of a haptic device, instead of physically adding clay masses to cultural heritage objects, to create built-in protection. In authors' previous paper [2] it is concluded that there are two reasons why the use of a haptic device for creating protection of 3D virtual models is a better solution. The first reason is to avoid physical contact with the artwork, and therefore eliminate the possibility of causing damage to it, and the second one is the reduction of execution time because it is not necessary to digitize the object two times (i.e., the original sculpture and the sculpture with added protection), as was the case in authors' previous research [2]. It is very important to have haptic feedback for precise and fine manipulation of 3D objects [15-17].

2 RELATED WORKS

In the current literature in the field, the most frequently mentioned method for incorporating protection into digital 3D models is the embedding of the so-called watermark. Embedding a watermark does not imply a specific method or process. For example, Kulkarni et al. [18] and Ahn et al. [19] presented a procedure in which embedding the watermark was done along the pre-defined axis, and 3D printing of this model must be performed along the same axis. Pham et al. [20] suggest cutting the model along the *Z*-axis and then embedding the watermark by changes over points on the model contour.

The same author stated that some of the previous research based on wavelet transformation [21] should make a difference between the embedding of protection in 3D digital models and in printed 3D models. Some of the approaches are based on the Gaussian function depending on which the parameter that defines the level of modification of the 3D virtual model is changed as Lee et al. presented in [22]. Hou et al. [23] reviewed intellectual property protection issues and solutions in the 3D printing world according to various scenarios. Beugnon et al. showed that it is also possible to encrypt 3D object binary formats [24]. Ivanova et al. [25] and Elliot et al. [26] presented methods for randomly adding dots to the 3D model's grid aimed to create protection known only to the manufacturer.

Haptic devices can be used for different purposes, and most often for training students in medicine and surgery. This type of device enables users to touch and manipulate

3D virtual objects in virtual environments and teleoperated systems, with the possibility of feeling the roughness of the surface they touch. Stamm, Altinsoy, and Merchel [27] used a haptic device with force feedback in a single point of contact to detect which geometric primitive it is. Ricardez et al. [28], Escobar-Castillejos et al. [29] and Qin [30] highlighted the cases of using two such devices at the same time for training young doctors in the field of surgery or using a haptic device for synchronization of manipulations in robotic joint surgeries. A virtual reality system that will help to accelerate the learning process of surgeons in the field of laparoscopic rectal surgery is presented by Pan et al. [31]. Hamza-Lupet al. [32] presented the most popular hardware and software components for developing haptic-based laparoscopic surgical training systems.

Yazdankhoo et al. [33] incorporated a neural network in a unilateral teleoperation system to predict the future position of the operator's hand online. Rećko et al. [34] created an integrated haptic device for upper limbs as a part of an exoskeletal system. Hamza-Lup et al. [35] created a cost-effective visual-haptic simulator for the liver tissue which allows for reducing skill acquisition time and risks.

Nikpour et al. [36] designed a unilateral teleoperation system, where neural networks were used to estimate the time delay of the communication channel based on the position and velocity of the master and slave robots (haptic devices). Another research aimed to estimate the time delay was created by Li et al. [37].

Haptic devices provide the user with a single point of contact to feel the surface roughness. According to this, Lee et al. [38] developed a tactile feedback system for virtual skin wrinkle simulation. Culbertson et al. [39] created a pen haptic texture toolkit for evaluating 100 haptic virtual textures and friction models. Papadopoulos et al. developed some type of algorithm [40] for identifying the friction and hardness of haptic surfaces for individuals with and without visual impairments. The method of using digital textures in close-range photogrammetry has recently been the subject of numerous investigations [41].

Fenz and Dirnberger designed [42] a training simulator with haptic interaction for real-time surgery simulation of intracranial aneurysm clipping with patient-specific geometries.

3 MATERIALS AND METHODS

Fig. 1 presents the proposed methodology of adding local, inconspicuous bumps on 3D digitized sculptures using a haptic device. The entrance point is a digital 3D model OS (Original Sculpture) without built-in protections obtained in previous research [2]. Virtual protection is added to the OS 3D model with the use of a haptic device, thus creating the OSP (Original Sculpture with Protection) 3D model. This kind of sculpting is much more reminiscent of traditional hand sculpting because there is physical resistance in contact with the digital model. In this way, it is possible to have better control over the amount of added material. The amount of added material tends to decrease, and it can be detected by comparing the 3D model with built-in protection and the original 3D model.

In the next step, 3D models of OS and OSP are printed on a 3D printer under the same conditions and settings. A 3D printer based on fused deposition modelling FDM technology is used for 3D printing with polylactic acid (PLA) material.

Then, the 3D printed models are scanned with a 3D scanner based on fringe projections, and OS1 and OSP1 3D models are created. To detect the built-in protection and measure the thickness of the added layer, a comparison of the digital 3D models is made using Computer Aided Inspection (CAI), because this technique is an easy way to estimate the geometrical accuracy of generated polygonal 3D models [43]. In the first step of CAI, the OS 3D model is compared with the OSP3D model where protection is added by the use of a haptic device. In the second step, a comparison is made between the two printed 3D models OS1 and OSP1.

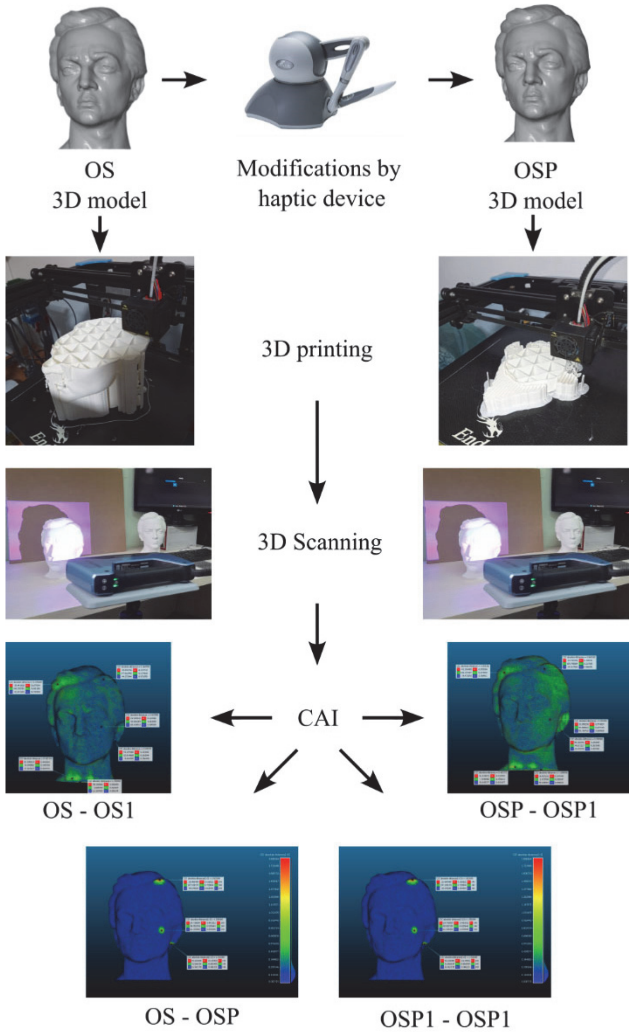

Figure 1 Proposed methodology of adding local, inconspicuous bumps on 3D digitized sculptures using a haptic device

This comparison aims to show that the built-in protection can be detected on printed models, regardless of the error that occurs during printing. To detect an error that occurred during printing, digital models OS and OSP are compared with the printed ones (i.e. their scans), namely, the original 3D model OS with the printed of that original OS1 (i.e. its scan), and the virtual 3D model with built-in protection OSP with its printed replica OSP1 (i.e. its scan). By using this methodology, 3D printing error is minimized because the final comparison compares two 3D models that are models obtained by scanning 3D printed models.

4 RESULTS
4.1 3D Modelling with a Haptic Device

Digitally added protection by adding material in software restricts the way a sculptor adds material. This kind of digital sculpting procedure by mouse gives appropriate results. However, its disadvantage is that it is not an intuitive way of sculpting, because of the lack of physical contact with the virtual 3D model. This fact led to the use of the Phantom Omni haptic device for digital sculpting in this research, for the purpose of embedding protection into a 3D virtual model. To create digital protection, i.e., built-in protection in form of local-inconspicuous bumps, the Phantom Omni haptic device shown in Fig. 2 was used.

Figure 2 Phantom Omni haptic device used for adding local-inconspicuous bumps

Tab. 1 shows the elementary characteristics of the device.

Table 1 The basic characteristics of the Phantom Omni haptic device

Device workspace	160 × 120 × 70 mm
Positioning accuracy	0.055 mm
Maximum force	3.3 N
Force generation	*x*, *y*, *z* direction
Positioning	*x*, *y*, *z* direction + three rotations
Interface for connecting to a computer	IEEE-1394 FireWire

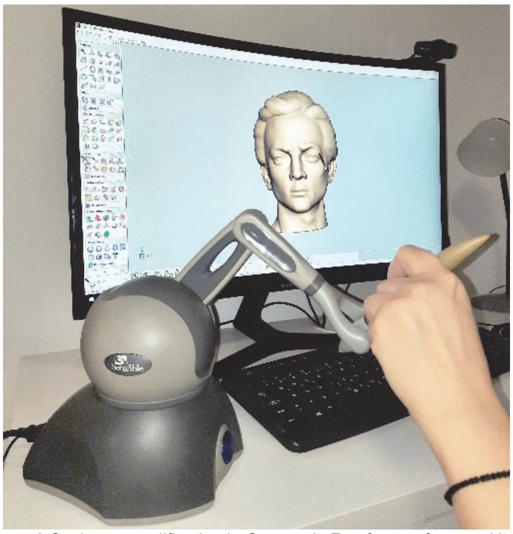

Figure 3 Sculpture modification in Geomagic Freeform software with the Phantom Omni haptic device

This device has a single point of contact in the pen, with the help of which the user achieves interaction, i.e., contact with the virtual 3D model, getting the impression of actually touching it. With the help of the force feedback, the user can get an impression of the shape of the geometry which is being touched, but also of the texture, especially with materials with an uneven surface. In digital sculpting, it is important to know how many layers of clay to add or subtract. In this particular case, it is essential to add a layer of clay to certain parts of the sculpture that will not be visible to an average observer and will not significantly change the character that is depicted. Fig. 3 shows the OS 3D model in Geomagic Freeform software, in which it was modified with the Phantom Omni haptic device.

In cooperation with the sculptor, a lock of hair, an earlobe, and a cheekbone (all three on the left side of the face) were chosen for the installation of protection [2]. Now, masses of clay were added at the same places, this time using the Phantom Omni haptic device [44]. Geomagic Freeform [45] software was used for this purpose. This software is specialized for digital sculpting with a haptic device. The combination of this software and the haptic device allowed the process of adding protection to a 3D virtual sculpture model to be more realistic and controlled than it was previously possible with a mouse. In the software, it is defined that the thickness of the added layer in one passage does not exceed 1.5 mm which means that if you modify the same area more than once, the thickness of the added layer may be greater. The final dimensions of the 3D model (OSP) were unchanged, Length × Width × Height ($L \times W \times H$) 150 × 180 × 220 mm.

4.2 3D Printing

The prepared 3D models OS and OSP are 3D printed with FDM additive technology, and the available 3D printer, Creality Ender 6, with a printing volume of 250 × 250 × 400 mm ($L \times W \times H$) [46]. 3D printing is a challenging process that involves several 3D printing setup parameters, such as:

- material,
- quality,
- support,
- travel and
- walls.

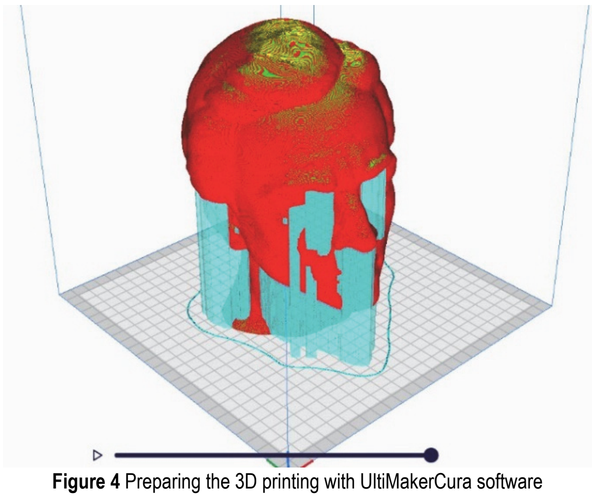

Figure 4 Preparing the 3D printing with UltiMakerCura software

Supported and available material polylactic acid (PLA) filament from Devil Design was used for 3D printing. The material is important as a 3D printing parameter because the build plate and the printing temperature must be adjusted based on the characteristics of the material. Those temperatures were set to 60 °C and 205 °C respectively. The quality of a 3D print is usually related to the height and width of the printing layer. The printing resolution used (layer height) of 0.2 mm is characterized by high precision and relatively smooth transitions between layers.

Fig. 4 shows the preparation of a 3D model for printing in UltiMakerCura software and the distribution of support structures around the 3D model.

Besides resolution and support, travel and walls are the parameters that influence 3D printing time. For optimal 3D printing speed and strength of 3D printing models, 6.5 mm retract distance of layer change and 1.5 mm wall thickness were used as 3D printing parameters. Final 3D printed models are shown in Fig. 5.

Figure 5 3D printed models OS (left) and OSP (right)

4.3 3D Scanning

The process of 3D scanning enables users to obtain 3D datasets and geometry of objects in high resolution at a very low cost [47]. The two 3D-printed models were scanned with EinScan Pro 2X scanner [48], which was also used for scanning the original sculpture [2]. The 3D scanning was done in fixed mode. This mode enables maximum guaranteed accuracy of 0.05 mm and a resolution of 0.2 mm. In this way, two new 3D models of the printed sculptures were obtained. The process of 3D scanning is shown in Fig. 6.

Because the 3D scanning area is small to cover the whole 3D printed model, the top half was scanned first, then the 3D scanner was put lower to cover the rest of the sculpture. The angle of rotation between the two scans was approximately between 15° and 25°, and the printed models were moved manually. In addition, several scans were made from the top and bottom side to cover the whole 3D model. Each complete 3D model was obtained by a fusion of 25 partial 3D scans.

Figure 6 The process of 3D scanning in fixed mode using EinScan Pro 2X optical 3D scanner

4.4 3D Models Comparison CAI

All comparisons of the 3D models were done in Cloud Compare [49] software. This software enables comparisons between two point clouds and represents the results in colour gradient graphical form as well as quantitative numerical form.

The results of the comparison of digital 3D models OS and OSP are shown in Fig. 7. As already mentioned, 3D virtual models, a model of the original sculpture OS, and a 3D model with built-in protection OSP by a haptic device were compared. It can be noticed that the thickness of the added layer has the highest value on the small area of the lock of hair and is 1.83 mm. Generally, the thickness of the additional layer does not exceed 1.5 mm, which is twice less than the added layer in previous research, and the use of the haptic device contributed to this. The feedback force that can be felt in the pen of the haptic device has contributed to a more realistic feel during digital sculpting and adding protection to a 3D model, thus providing better control over the amount of layer being added.

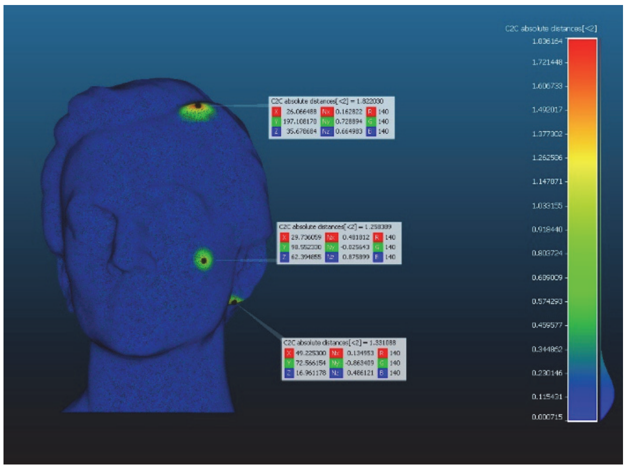

Figure 7 Results of the comparison of digital 3D models in CloudCompare software (OS and OSP)

To detect built-in protection on the printed model, a comparison of the printed models, originals OS1, and 3D models with built-in protection OSP1 was made. The results of this comparison are shown in Fig. 8. The representation and arrangement of colours on the model, as well as on the histogram, already give us visual information that the values measured are similar to the values in the comparison of digital 3D models. In this case, the highest value for the thickness of the added layer on the lock of hair was also measured and is 1.89 mm. The difference in the measured values depends on the error that occurred during the 3D printing and it was expected that the measured values, in this case, will not match 100% with the measured values of the virtual 3D models.

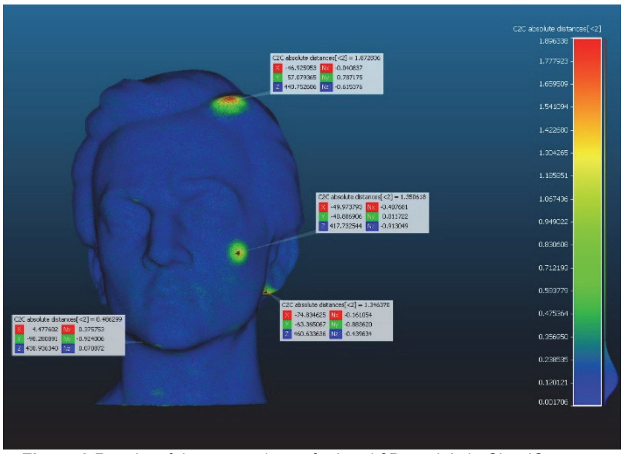

Figure 8 Results of the comparison of printed 3D models in CloudCompare software (OS1 and OSP1)

The comparison of virtual and printed models (OS - OS1) involves comparing the original models of the sculpture, i.e., without built-in protection. This means that the original virtual 3D model of the sculpture OS was compared with its printed replica OS1.

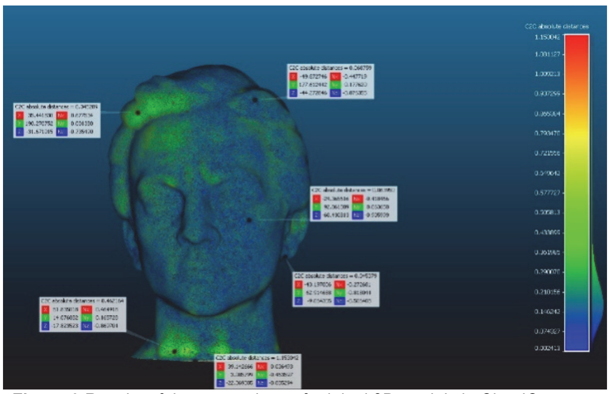

Figure 9 Results of the comparison of original 3D models in CloudCompare software (virtual (OS) and printed (OS1))

Fig. 9 shows the results of the comparison of these two models. On the histogram, it can be seen that the largest value concerning the difference between the models is 1.15 mm. The points that have this value are marked in red on the model and are located at the bottom of the sculpture if we look at it from the front. That is, these are the points located at the intersection of the neck of the figure and the horizontal plane that represents the bottom of the sculpture. The range of the generated error is from 0.002 mm to 0.4 mm, that is, the error in this range was generated at most points of the model, which can be seen on the histogram. The model is dominated by dark blue color, and these are the points that have an error of less than 0.2 mm. The parts of the sculpture that authors are interested in (the strand of hair, the earlobe, and the cheekbone, all on the left side of the face) have an error generated during printing of less than 0.1 mm.

The last comparison of 3D models with built-in protection (virtual and printed model) OSP - OSP1 has the same aim as the previous one, i.e., to identify errors generated during printing 3D models, and in this step 3D models with built-in protection, virtual OSP and printed OSP1 (i.e., its scan) are compared. The values measured in this case are shown in Fig. 10. Similar values for the generated error during printing were obtained as in the previous case. The highest measured value is 1mm. The error in the areas of the face that are of interest to us is about 0.1 mm. Most points of the 3D model have a generated error between 0.001 mm and 0.40 mm.

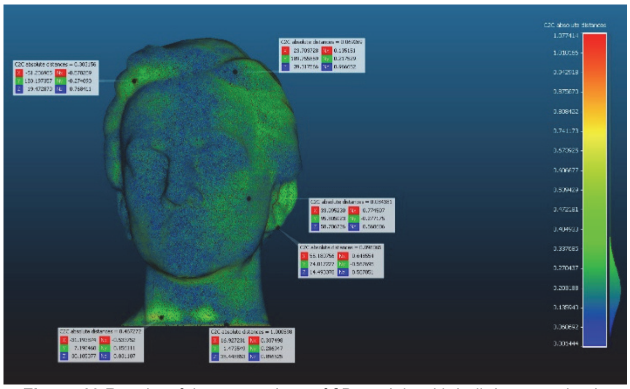

Figure 10 Results of the comparison of 3D models with built-in protection in CloudCompare software (virtual (OSP) and printed (OSP1))

5 DISCUSSION

In this research, authors considered four digital models: a digital model of the original sculpture OS, a digital sculpture model with built-in protection OSP, as well as a scan-printed sculpture obtained by printing the OS model (OS1), and a scan-printed sculpture obtained by printing the OSP model (OSP1). Then comparisons were made to detect differences in the geometry of the following pairs of sculptures: OS and OSP, OS1 and OSP1, then OS and OS1, as well as OSP and OSP1. This was done to state the following: when comparing OS and OSP, it is possible to easily detect the zones where the material was added, as well as the thickness of its layer. By comparing OS1 and OSP1, authors wanted to show that the areas where the material was added to protect the original model are also noticeable on the printed models. By comparing OS and OS1 authors wanted to prove that the digital model of the original sculpture is very similar to the scan of the printed sculpture. And by comparing OSP and OSP1, authors wanted to prove that the digital's sculpture model with built-in protection is very similar to the scan of its printed replica. In this way, it is provided that even by comparing the printed models, it is possible to determine which of them was obtained by printing the original 3D sculpture, and which is a forgery. It has been proven that the digital sculpting procedure using a haptic device has an advantage over digital sculpting with a mouse because the haptic device provides appropriate physical resistance at the moment of contact with the sculpture, which is associated with a realistic sculpting procedure. In this way, the sensibility of the person who digitally sculpts is increased, and consequently, the amount of added material in the selected places is twice as small compared to the amount of material authors had in their previous research.

Comparing the models OS and OSP, OS1 and OSP1, OS and OS1, OSP and OSP1 showed that the differences measured by the software CloudCompare (minimum 0.002 mm) are such that it shows about 10 times more accurate error compared to the precision of the scanner EinScan Pro (0.05 mm). As all four models were scanned with the same scanner, the same error was generated on all four digital models, therefore the precision of the scanner has no influence on the difference interval between the models that were compared in the four cases mentioned, in the same software. It is important to have a tendency to clearly detect the area in which protection has been added by comparison.

6 CONCLUSIONS

The idea of this paper is to improve the authors' approach described in paper [2], in which a new approach for the protection of digitized cultural heritage was presented. The idea was illustrated using an example of a human head sculpture, and the same idea can be applied to any artistic or architectural work, that is, a 3D model. The novelty in this work is that digital protection is added using a haptic device, which is a more friendly digital sculpting procedure compared to mouse sculpting. Another novelty is that both models were printed, a digitized model of the original sculpture and a 3D model with built-in protection. Next, those two printed sculptures were scanned and by comparing the two 3D models obtained in this way the areas where the protection was added were located. In this way, the authors' hypothesis that it is possible to state which sculpture was obtained by printing the original 3D model, and which was obtained by printing the 3D model with built-in protection, was confirmed. In this way, it was determined which sculpture is an original and which is a forgery.

6.1 Possibility for Future Research

In recent years, haptic devices have advanced significantly, so there are so-called haptic hands. A haptic hand is a robotic hand whose design is simplified and created to imitate the human hand and provide haptic force feedback in all joints at the moment of contact with an object in the virtual environment [42, 50-59]. Authors feel that using a haptic hand for digital sculpting and adding protection would allow for a more realistic sculpting experience than what was achieved with the haptic device used in this research. As a haptic hand uses a whole hand, such sculpting is the digital equivalent of real sculpting because user interacts with the virtual 3D model with each finger and each segment of the finger, that is, the joint where the appropriate resistance is achieved. The haptic device, used in this research, contains a pen that is moved most often by holding it with three fingers, and yet this does not fully correspond to the process of real sculpting.

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