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PHOTOGRAMMETRY FOR 3D RECONSTRUCTION OF OBJECTS: EFFECTS OF GEOMETRY, TEXTURE AND PHOTOGRAPHING

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ABSTRACT

Today, the use of 3D scanning methods is increasing in a wide range of industries from biomedical to game production. The photogrammetry method is in demand by 3D scanning users due to its portability, photo-realistic textured modeling, and low cost. Scanned objects vary according to industries and can have various materials, geometries and textures. In order to better benefit from the advantages of the photogrammetry method, it is necessary to know the response of the method against different parameters. Unlike the studies in the literature, in this study, many objects with various geometries, different materials and textures were reconstructed and evaluated by using the same equipment and workflow in the same environment, and thus a fair evaluation was performed for various factors affecting the reconstruction process. In this context, 24 differently shaped objects with metal, fabric, plastic, wood, glass, ceramic and organic textures were reconstructed. A comprehensive evaluation was conducted on the solid and textured models generated from the objects. In addition to the effects of object geometry, texture properties, photo shooting angle and distance, it also sought answers to questions about factors affecting the accuracy and mesh quality of the 3D models. In this study, it is possible to find some recent specific results and validated general results together related to photogrammetric modeling.

Keywords: 3D reconstruction; 3D scanning; image-based modeling; photo-scan; photogrammetry; texture.

INTRODUCTION

The use of three-dimensional (3D) scanning, which has been the popular research subject of recent years, is rapidly spreading in many different fields such as engineering (Reyno *et al.*, 2018, Wang *et al.*, 2018), quality control (Helle and Lemu, 2021), biomedical (Manuel *et al.*, 2017, Surmen and Arslan, 2021), architecture (Xu *et al.*, 2017), archeology (Calin *et al.*, 2015), documentation (Villa, 2017), AR / VR (Koller *et al.*, 2019) , entertainment (Statham, 2020), education (Lee *et al.*, 2019). 3D reconstruction of free-form objects that are difficult to model with computer-aided design (CAD) software can be generated using 3D scanning technology. Laser triangulation scanning (Calin *et al.*, 2015), structured light 3D scanning (Cekus *et al.*, 2021), contact-based 3D scanning (Ardelean and Năsui, 2021) and 3D photogrammetry (Koller *et al.*, 2019, Orun *et al.*, 2018, Surmen *et al.*, 2016, Wang *et al.*, 2018) are the main methods used to scan objects in three dimensions. Each method has its own superior features and for different applications, the most appropriate method should be selected by considering these features. It is necessary to know the potentials and limitations of the methods well to avoid both time and financial losses.

Low cost, portability, color scanning, suitability for different sized objects and indoor and outdoor use are among the main features of 3D photogrammetry. The 3D photogrammetry method is known as the image-based 3D modeling method (Remondino *et al.*, 2005) or "photogrammetric 3D scanning" (Reljić *et al.*, 2019) that enables the generation of a 3D model of an object by combining the object's photographs taken from different angles. This technique consists of three basic stages: photographing, generating the 3D model by combining the photographs with computer software and optionally editing the model. However, there are some critical issues for successfully modeling objects. The material, texture and geometric properties of objects greatly affect the success of 3D modeling. In addition, photographing, which is the most critical step of the 3D photogrammetry method consisting of parameters such as photo shooting angle, distance and shooting environment, directly affects the production of 3D models. It is very important to know the problems that may be encountered in the 3D reconstruction process with photogrammetry and to take measures against them in order to prevent the loss of time and to produce successful models. In this study, the effects of object parameters such as geometry, material and texture; and on photographing such as photo shooting angles, distance and environmental conditions were investigated. The effects of these parameters have been demonstrated and evaluated by reconstructing 24 different shaped objects with metal, fabric, plastic, wood, glass, ceramic and organic textures.

In this study, Autodesk ReCap Photo software, which uses cloud technology and generates textured mesh models, was used in the reconstruction of objects. Solid and textured model pictures of each 3D model obtained without applying any editing process are shared in the paper. Based on the results, 3D models of objects produced by 3D photogrammetry were comprehensively evaluated in terms of visual accuracy, effects of object geometry, object texture, photo shooting angle, environment conditions, and mesh quality. Unlike the studies in the literature, with this study, reconstructions of parts with various geometries with diverse materials were made with the same method, equipment and in the same environment, and thus a fair evaluation was made for different parameters. This paper will contribute to improving the use of photogrammetry for 3D reconstruction in terms of testing various factors affecting photogrammetry and presenting the results together.

METHODS

PROCESS AND SYSTEM SETUP OF PHOTOGRAMMETRIC 3D MODELING

One of the main approaches used in photogrammetry to reconstruct the 3D geometry of an object from a set of 2D images is Structure from Motion (SfM). In this approach, the 3D structure of an object and the motion of a camera is determined using a sequence of overlapping images taken by a moving camera. Equivalently, it can be thought of the object as moving and the camera is stationary; see (Özyeşil *et al.*, 2017) for further details. The photogrammetric 3D Modeling process generally consists of photo shooting, 3D model generation and post-processing steps (Fig. 1). The first stage, photographing, is the most critical. At this stage, the photographs of the object should partially overlap with each other (Hess *et al.*, 2017). The next stage is generating 3D models of the objects. The captured photos are transferred to the software after they are uploaded to the computer. If the software is web-based, the speed of this process varies depending on the upload speed. In addition, the start of modeling can sometimes take time due to the queue in the cloud system. After the photos are uploaded online, the polygon, solid and textured models can be generated automatically in Autodesk ReCap Photo software. After the model is obtained, the post-processing stage including basic editing operations such as cutting, surface smoothing and hole filling can be performed optionally in the software's editor mode. However, in this study, no editing operation was performed on the models to be able to directly compare the models generated by the 3D photogrammetry method.

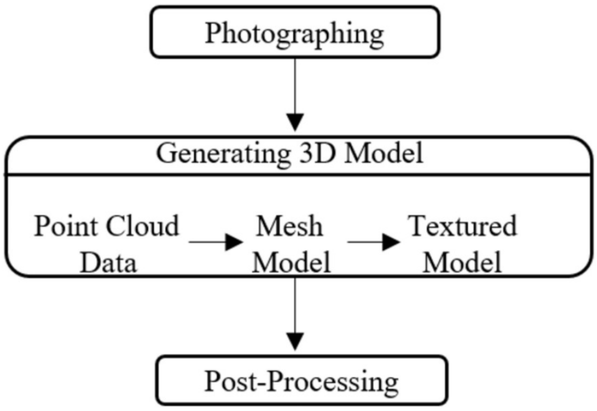


Fig. 1. *Photogrammetric 3D Modeling process.*

A turntable platform has been produced to overlap the photographs of the object at a reasonable rate (more than 80%) during the photo-shooting phase. This platform can be rotated manually to the desired angle (Fig. 2).

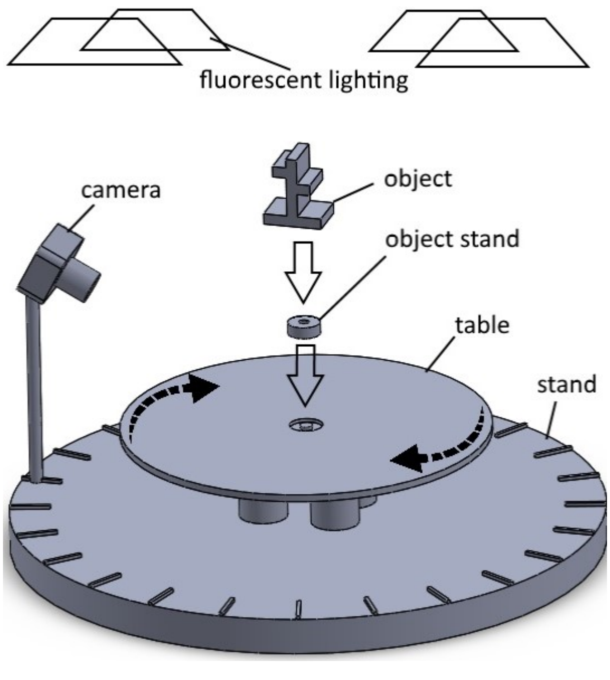


Fig. 2. *System setup for 3D photogrammetry applications.*

This feature provides the opportunity to adjust the angle of rotation according to the geometric detail of the object. While the platform is rotated at smaller angles in highly detailed geometric parts, it is rotated at wider angles for less detailed parts, thus more cost-effective results can be obtained. There is a fixed stand on which the turntable platform is placed. 360° angles are marked as reference points on this stand. There is another small stand in the center of the turntable platform where the object is placed. In this system, while the camera is stationary, the object is rotated at certain angles by means of the turntable platform, the photograph of the object is taken after each rotation and the photographing is completed at the end of one full tour. Since the direction of the camera does not change, the conditions of light and background remain as they were originally set. A closed room was preferred for photographing to control shadows, reflection and glare easily. A dark-colored, non-glare and anti-reflection fabric was used for the background in the study.

Fig. 3. *Objects used for 3D reconstruction applications in the study.*

OBJECTS USED IN THE STUDY FOR 3D RECONSTRUCTION

To better understand the limits and potentials of 3D photogrammetry, sample objects with various geometries and textures were chosen for 3D reconstruction applications.

The texture and material of objects that determine properties such as brightness, transparency, opacity, roughness, and reflection directly affect the success of the 3D photogrammetry process. Also, geometric details such as rounded edges, cylindrical surfaces, channels and thickness are other object-oriented parameters that affect this success. Therefore, in this study, 24 objects with different geometric features made of plastic, metal, fabric, wood and organic materials were modeled using 3D photogrammetry to see the effects of the shape and texture of the objects. These objects were chosen among industrial products, organic objects, clothes and ornaments. The pictures of the objects used in the study are shown in Fig. 3.

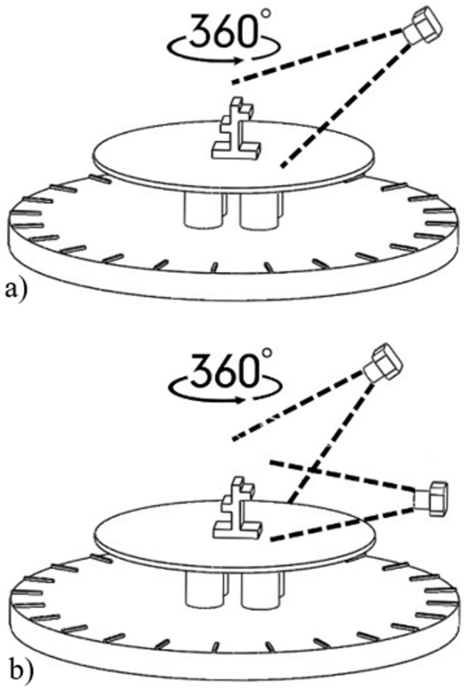


Fig. 4. *Vertical shooting angles used in photographing: a) Single vertical angle shooting (35°). b) Dual vertical angle shooting (0° and 45°).*

PHOTOGRAPHING

In the study, photographs of the objects were taken using a Canon EOS 50D brand camera and an 18-135 mm lens. The camera was positioned at a distance of approximately 40 cm from the object. For single vertical angle shootings, the camera was fixed at an approximate vertical angle of 35° (Fig. 4(a)) and usually, 24 photos were taken for each object. The shots were repeated by rotating the platform 15° about its axis. The method used in this work was inspired by the photo sculpting technique (Bourell *et* *al.*, 2014) used in the 19th century to make exact three-dimensional copies of any object.

For more detailed objects, the shooting frequency can be increased by decreasing the horizontal angle. In the study, 48 photos were taken by rotating the platform 7.5° for detailed parts. The images used to generate 3D models generally provided around 80% overlap between each other. However, it may not be possible to obtain better results by simply increasing the number of photos in horizontal angles. All surfaces of the model should be described with images to reconstruct the object properly. Sometimes a single vertical shooting angle may not be sufficient to capture all the surfaces of the object. In such cases, two different vertical photo angles were determined, one opposite the object and the other 45° (Fig. 4(b)). In this way, photographs of 24 different objects were taken and solid and textured 3D models of objects were created to evaluate the effects of visual accuracy, object geometry and texture properties. . In this study, the effects of shooting distance, image number and resolution were also investigated besides the effects of object texture, geometry and material on photogrammetry. In order to observe the effects of these three parameters on mesh quality, three 3D models of the same object (Object 9) were generated and compared with each other by keeping two of the parameters fixed and changing one parameter. The variables are determined as 3.7 megapixels and 15.1 megapixels for resolution, 30 cm and 120 cm for distance, and 24 and 48 for the number of images. The results are shared under the title of "Mesh Quality".

In addition, an intuitive method was carried out for improving the geometric accuracy. It was investigated whether the geometric accuracy of the 3D model produced by marking the surface boundaries of an object could be improved. The boundaries of Object 17 are marked and Object 18 was obtained by marking the borders of the object with a marker. The reconstruction process of the object was performed and compared to its unmarked 3D model.

One of the important parameters in photogrammetry is glossiness. Glossiness is a factor that negatively affects photogrammetry, especially in metal and smooth objects. In order to investigate the effect of ISO value on geometric accuracy, photogrammetric models were created for a metal object (Object 22) with two different ISO values. In addition, the surface of the same object was covered with powder and mattified. 3D models obtained with different ISO values and mattifying were compared and their geometric accuracy was observed.

RECAP PHOTO SOFTWARE

ReCap Photo is a cloud-based software developed by Autodesk as an alternative to 3D photogrammetry software of Autodesk such as 123D Catch (Surmen *et al.*, 2016, Wang *et al.*, 2018), ReMake (Lamb *et al.*, 2018) and ReCap 360 (Peterman and Barton, 2017), which have been used in many scientific articles before. It has aerial and object modeling options and also an editor mode. ReCap Photo has an education version which can be used for academic purposes.

For 3D photogrammetry applications, there are other software alternatives such as Agisoft Metashape (Agisoft LLC), 3DF Zephyr (3Dflow SRL.), Meshroom (AliceVision) besides ReCap Photo (Autodesk Inc.). Reconstruction software generally performs four steps that consist of elimination of erroneous data, determination of the global topology of the object's surface, generation of the polygonal surface and editing of the model (Remondino, 2003). These processes require a high-capacity computer. However, ReCap Photo can be run on low-equipped computers thanks to its web-based nature. The computer used in the study has an Intel Core i5-5200U CPU, 2.20 GHz processor and 8.00 GB RAM. The 3D reconstruction process takes a while depending on the number of photographs. After the process is completed, the 3D model file can be saved to desktop computers in an RCM format. In addition, after the model is obtained, there are tools in the editor mode of the software to repair and retopologize surface defects. In editor mode, it is possible to use the diagnostic tool to detect issues. Furthermore, the model file can be exported in OBJ., FBX., STL., PLY., and PTS. formats to work on the model in more detail using other software.

RESULTS AND DISCUSSION

VISUAL ACCURACY

In this section, solid and textured models of 24 objects produced with 3D photogrammetry are presented in Fig. 5 and evaluated in terms of visual accuracy. The effects of material properties such as opacity, glossiness, reflection, transparency and geometric properties of the object such as wall thickness, edge and surface shapes on the reconstruction process were investigated, and the models produced were compared with each other considering their geometric and texture properties. Based on the evaluation of the 3D models produced in the present study, the following points were observed:

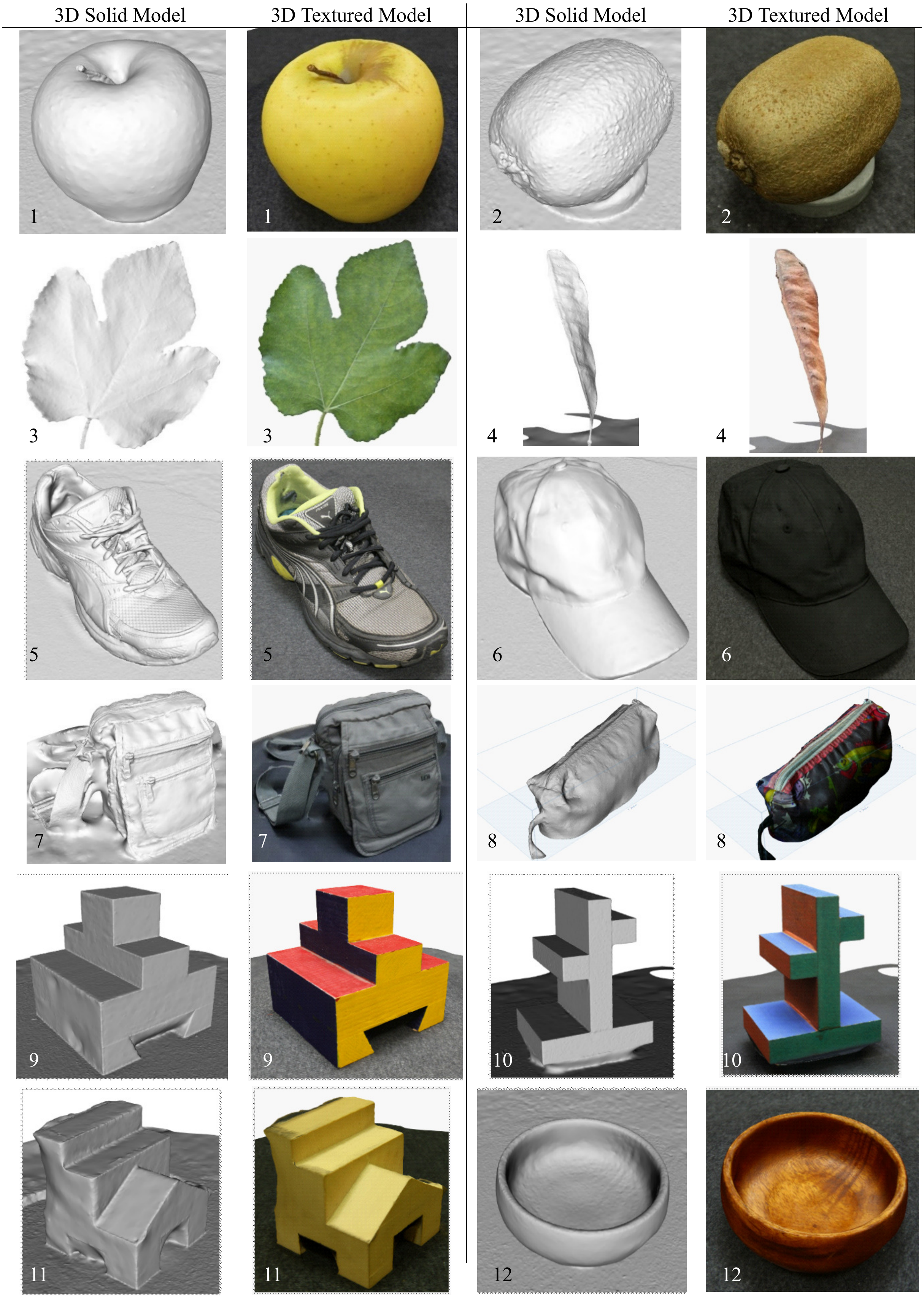
• The organic objects used in the study could be modeled very successfully with the 3D Photogrammetry method due to their featured textures (Objects 1-4).
• Objects with non-reflective and featured textures, such as fabrics, could be modeled with high success like organic objects, although they have very detailed geometries (Objects 5-8).
• Wooden and painted wooden objects can also be counted among successfully modeled objects (Objects 9-12). However, regional defects were observed in wooden objects with sanded surfaces (Object 11).
• In the reconstruction of the objects with letters, numbers and patterns on their surfaces, it was observed that these parts were modeled in relief (Objects 12-14).
• Plastic objects are more difficult to model with the increased smoothness and gloss levels of their surfaces (Objects 15-17). In addition, smoothness causes some surface defects to occur even in objects with matte surfaces.
• Transparent objects are not suitable for 3D photogrammetry (Objects 19, 20). Transparent objects can be modeled if their surfaces are coated with powder or matte spray (Object 21).
• Metal objects can be modeled with medium geometric accuracy according to lighting conditions (Object 22). Coating application increases the success rate in modeling metal objects (Object 23).
• Objects made of ceramic and clay can be modeled successfully (Objects 18, 24). Although the clay object has a very detailed geometry, it was able to be modeled more successfully than the ceramic object with shiny surfaces thanks to its matte surface.

EFFECT OF OBJECT GEOMETRY AND TEXTURE

The objects reconstructed in this study have many different geometric features such as flat and rounded edges, flat and curved surfaces, grooves, protrusions and cavities. The curved surfaces and rounded edges reflect the light in many directions and seem glossy. This is a factor that negatively affects 3D reconstruction. Moreover, if objects with rounded edges and curved surfaces have a smooth texture, the success of 3D reconstruction decreases even more. It is possible to observe this case when we examine model 15 in Fig.5. The 3D reconstruction process was repeated by doubling the number of photographs for object 15, but this did not improve the result. However, increasing the number of photographs and shooting frequency for objects with detailed geometry will provide a model with higher geometric accuracy as explained in the next topic. On the other hand, it is seen in Fig. 5 that the grooves in models 9 and 11 could not be obtained properly. The grooves are mostly under an intense shade, so the interiors are modeled as partially filled.

Although some geometric features such as detailed surface shapes, curved surfaces and rounded edges affect the 3D photogrammetry process negatively, some texture types can tolerate this case and increase the success of reconstruction. When we examine the solid and textured models of object 24 made of clay in Fig. 5, we can see that the result is quite successful even though the object has a very complex geometry, many rounded edges and curved surfaces. The texture and color of the model were obtained in a very realistic way besides its geometry, although the model was generated with a total of 48 photographs taken from only 2 different vertical angles. It is understood that clay material such as stone and gypsum is also very suitable for 3D photogrammetry due to its rough and featured texture. Even the complex geometry of the objects made of these materials does not cause a significant negative effect on the reconstruction of the model. Therefore, 3D photogrammetry is very suitable for the reconstruction of objects in the fields of archeology and architecture (Douglass *et al.*, 2015). In addition, very good results can be obtained for organic textured objects. As seen in Fig. 3, objects 1-4 have rounded edges, curved surfaces and detailed geometries and objects 1, 2 also have shining curved surfaces. The 3D solid and textured models of these objects were successfully obtained in terms of geometric and visual accuracy (Fig 5). Although fabric-textured objects 5-7 have very complex geometries, they could be modeled in detail with only 48 photographs. It is understood that fabric textures facilitate the 3D photogrammetry process. By taking advantage, it may be possible to develop patient-specific biomedical products with 3D photogrammetry (Surmen *et al.*, 2016). Undoubtedly, the featured and rough textures of the objects could tolerate the geometric disadvantages of the objects.

Metal objects are not easy to model with 3D photogrammetry due to their shiny, smooth surfaces. Nevertheless, Object 22 (Fig. 3) could be modeled with photographs taken by lowering the ISO value of the camera as shown in Fig. 5 (model 22). The 3D models produced from the photographs of object 22 by adjusting the ISO value of the camera to 2500 and 800 are shown in Fig. 6. Increasing and decreasing the ISO value of the camera according to the intensity of the light reflected from the object affects the success of the 3D reconstruction process.


3D Solid Model
3D Textured Model
3D Solid Model
3D Textured Model
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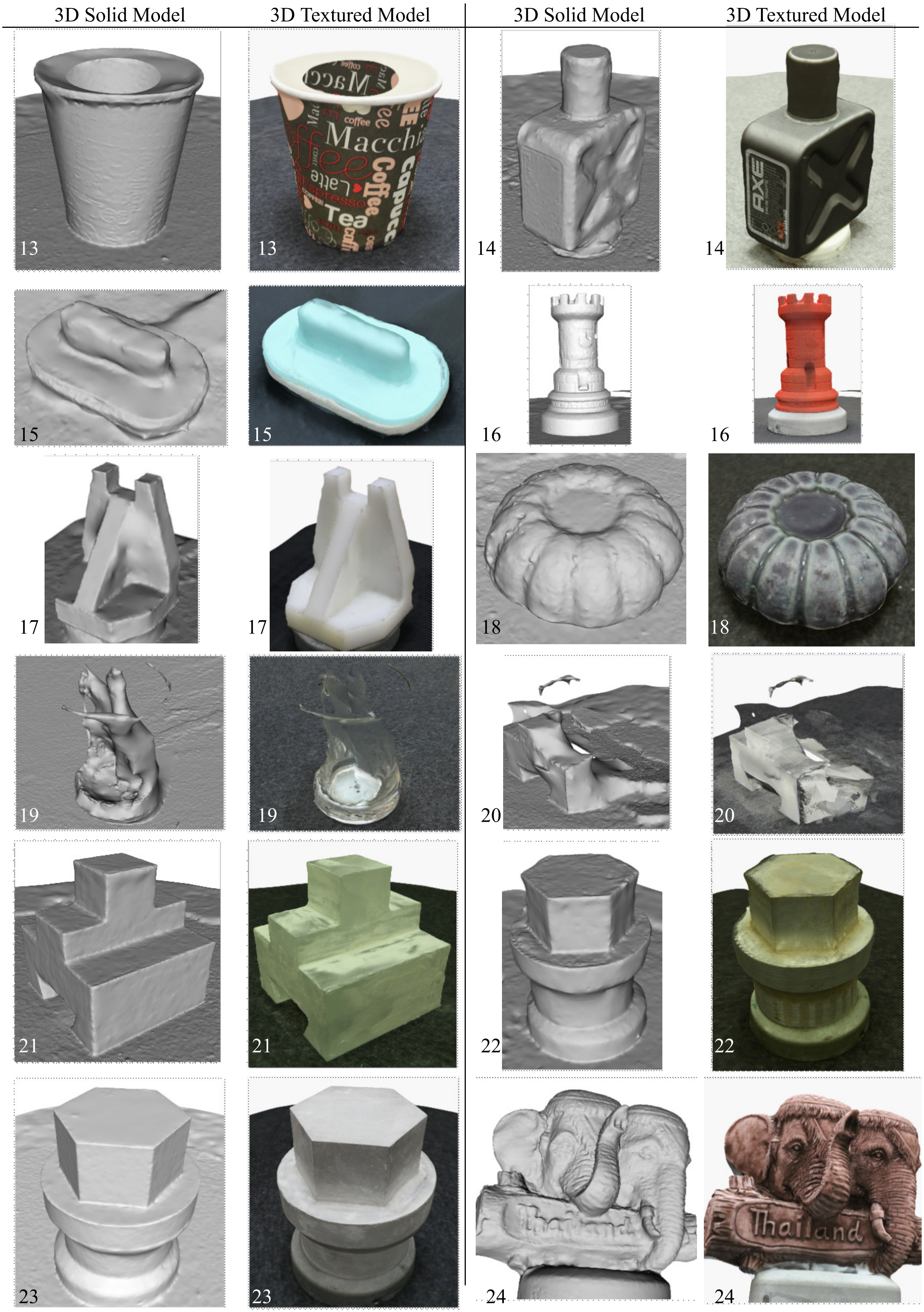

Fig. 5. *Solid and textured 3D models of the objects generated with 3D photogrammetry.*

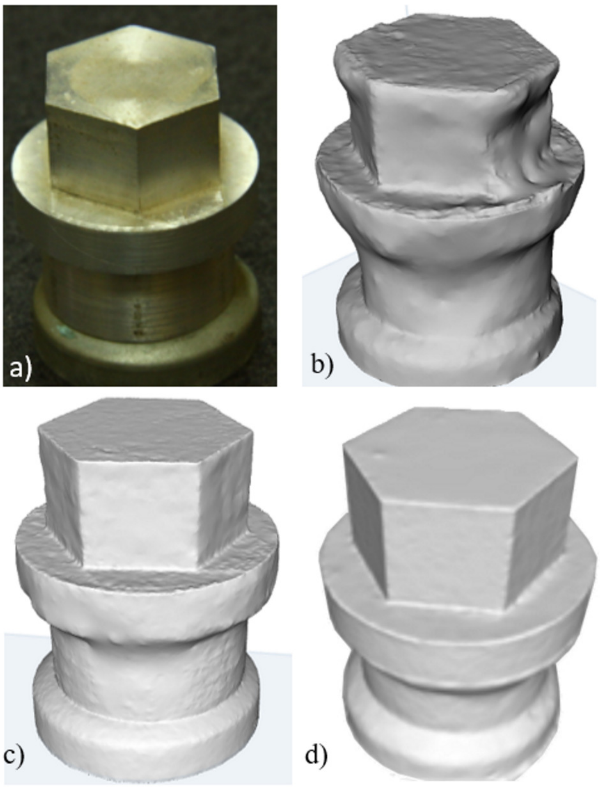

Fig. 6. *The effect of ISO on object 22 made of metal and powder-coating: a) Object 22. b) 3D solid model of object 22 at ISO 2500. c) 3D solid model of object 22 at ISO 800. d) 3D solid model of the powder-coated version of the object.*

In addition, coating the surface of metal objects with a matte material increases geometric accuracy. Fig. 6d shows the 3D model of the powder-coated version of the same metal object generated by 3D photogrammetry. It was not possible to obtain 3D models of glass and transparent objects correctly without applying the coating process by the photogrammetry method (Fig. 4 (model 19, 20)). Transparent objects can be modeled by coating them with a material such as powder that prevents the transmission of light (Fig. 4 (model 21)). Objects 11 and 15 could not be modeled very accurately, although they are not made of metal or glass (Fig. 4 (model 11, 15)). But their surfaces are quite smooth. Whether the object's texture is metal, wood, or plastic, the surface roughness causes a significant effect on reconstruction.

It has been observed that the color differences of the surfaces in some objects affect the 3D reconstruction process. It can be seen in Fig. 7a and Fig. 7b that different colored lines on the wooden material in object 12 and various colored figures in object 13 are modeled as reliefs. These minor surface problems can be solved with simple post-processing operations.

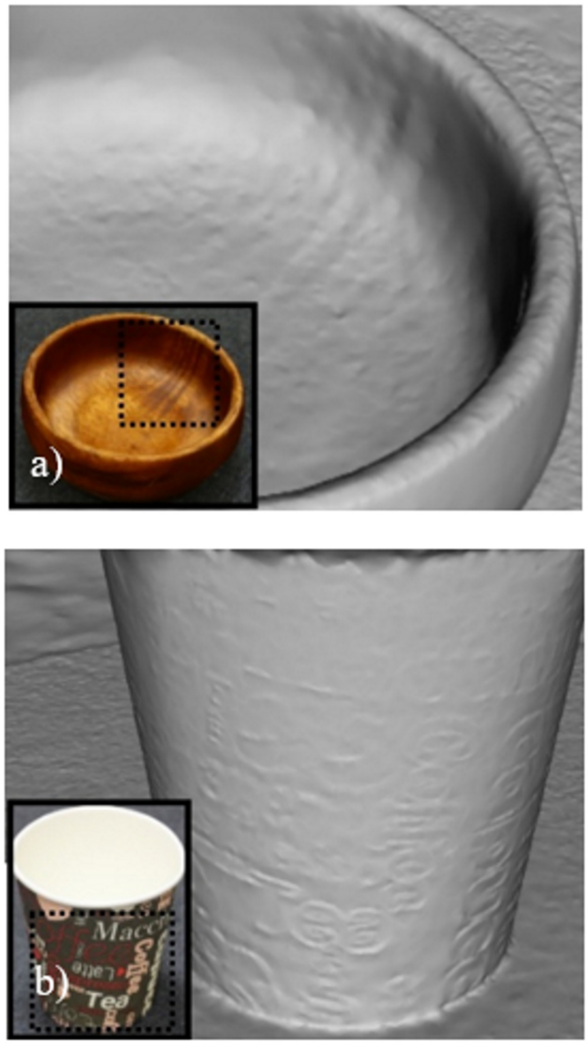

Fig. 7. *The effect of figures on texture. a) Object 12 and its solid model. b) Object 13 and its solid model.*

On the other hand, this case suggests that the effect of color difference can be used positively to improve results in various applications. There are some studies on labeling with 2D photo-editing tools on the pictures of the object (Stathopoulou and Remondino, 2019, Ziegler *et al.*, 2003). Unlike these studies, in the following example (object 17), physical labeling was applied directly to the object. As shown in Fig. 8c, the edges of object 17 were drawn with a marker and made clear. Therefore, object 17 could be reconstructed with higher geometric accuracy (Fig. 8d). The geometric accuracy was developed along the drawn lines and this reflected positively on the surfaces. Labeling the edges of the surfaces with a marker on the object can make an important contribution to the improvement of 3D reconstruction results.

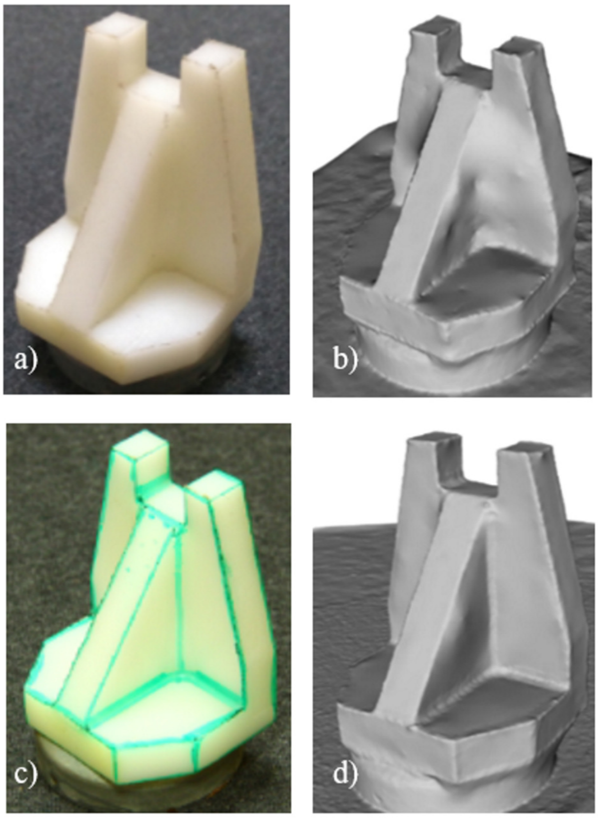

Fig. 8. *Improving a model with labeling: a) Object 17. b) Solid model of object 17. c) The object with outlined edges. d) Solid model of the object with outlined edges.*

EFFECTS OF SHOOTING ANGLE

In 3D reconstruction applications using the photogrammetry method, it is necessary to take photographs of all surfaces of the object to model the object correctly. It has been seen in the applications that there are holes on surfaces that cannot be photographed and swollen surfaces in shaded areas. Therefore, it may be necessary to take pictures at different vertical angles. Fig. 9 shows two reconstructed 3D models of object 10. The first model (Fig. 9b) was generated from 24 photographs taken from a single vertical angle using the method shown in Fig. 4(a). In this model, invisible and shaded surfaces under the wing parts of the object were modeled as holes and swollen surfaces. The second model was produced by taking a total of 48 photographs from two different angles, one with a vertical angle of 45° and the other directly in front of the object, using the method shown in Fig. 4b. Thus, the geometric accuracy of the model has been increased by eliminating the surface defects (Fig. 9(c)).

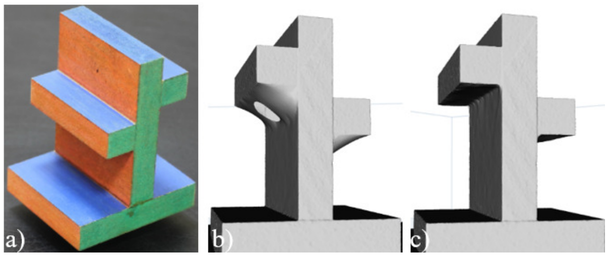

Fig. 9. *The effect of increasing the number of vertical shooting angles on object 10: a) Object 10. b) 3D model obtained with photographs taken from a single vertical angle. c) 3D model obtained with photographs taken from dual vertical angles.*

In the study, two different leaf objects (objects 3, 4) were reconstructed with the 3D photogrammetry method and an important point to be considered for photographing stage was discovered in modeling such very thin objects. it can be thought that objects without a significant wall thickness can be modeled with photographs taken from a right angle. However, this method causes some surface problems.

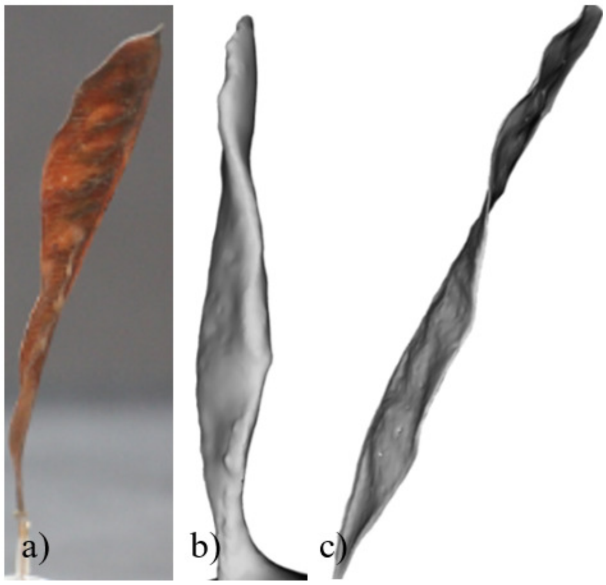

Fig. 10. *Reconstruction of a thin object: a) Object 4. b) Right angle shot. c) 30° angle shot.*

Fig. 10b shows a solid model of a seedpod (object 4) modeled with 24 pictures taken from the right angle. It is seen that the surfaces of the produced model are swollen and the model has a greater wall thickness than the real object. The object is modeled with a higher geometric accuracy using 24 photographs taken at an angle of 30° instead of a right angle (Fig. 10c). The same problem was observed for object 3 and the problem was solved with the same method. In this way, not only the wall thickness of the object but also the surface details could be reconstructed more accurately.

EFFECTS OF ENVIRONMENTAL CONDITIONS ON SHOOTING

Throughout the reconstruction applications, It has been observed that lighting conditions, shadows, refraction, reflections, and immobility of the object are the most important issues to be considered in the photographing phase. External factors such as daylight and wind can be prevented in the indoor shooting. Although taking advantage of daylight seems like a good idea, the intensity of daylight may vary for each shot. Daylight entering through the window and the shadows of other objects in the environment may adversely affect the photographs and cause the software to fail in the image definition stage before starting the modeling process. Another idea for lighting could be spotlights placed at different angles around the object. But this illumination should not cause any shadow on the object and the light should be softened and precisely adjusted. In this study, the shots were made in a closed room with no exterior light, using a turntable platform and a fluorescent lighting system placed above the platform, a dark-colored fabric for the background, and the floor to achieve a high level of environmental control. In addition, it should be preferred that the background and the floor are matte and blank to obtain healthy photos for 3D photogrammetry. Also, the background should be large enough for low and high-angle shots.

In 3D photogrammetry, two methods are generally used for the photographing phase. The first method is to take pictures from different angles by rotating around the object (Surmen *et al.*, 2016, Wang *et al.*, 2018). In this method, conditions of the lighting and background will change in every photo shoot and the photo quality may be negatively affected. Since environmental control is difficult in this method, photographs should be taken with great care. The second method, used in this study, is to take pictures of the object by rotating the object around its axis while the camera is stationary. The background, floor and lighting conditions remain constant in each photoshoot. Thus, the preparation of environmental conditions for single shooting angle can also be used for other shooting angles. Another point during the photoshoot is that the limbs belonging to the object should be fixed. External effects such as wind can be prevented during interior shooting, but some objects such as leaves may move during the rotation of the object on the rotatable platform. In such cases, extra precautions may be taken to fix the object.

MESH QUALITY

The effects of image resolution, shooting distance and image number on the mesh quality of the generated model were evaluated by comparing the models with different features generated from object 9. A new 3D model was generated from object 9 for each parameter to evaluate parameters independently. In total, three models were generated and two parameters were kept constant and one parameter was changed in each model and the results were compared considering the number of faces and vertices. The parameters were determined as 3.7 megapixels (M) (2352 x 1568 pixels) and 15.1 M (4752 x 3168 pixels) for resolution, 30 cm and 120 cm for distance, 24 and 48 for the number of images.

Firstly, two models of object 9 were generated with 3.7 M and 15.1 M resolution photographs to investigate the effect of photo resolution. 24 photographs of the object were taken from the same distance. The vertices and faces were determined in the editor interface of ReCap Photo software by following the path “Method of analyze”, “Mesh report”. The number of vertices is 21422, the number of faces is 36632 for the first model, the number of vertices is 69039, and number of faces is 123359 for the second model. The image resolution directly affected the mesh quality. It is seen that the model obtained with high resolution (15.1 M) images has 3.2 times the number of vertices and 3.4 times the number of polygons compared to the model obtained with lower resolution (3.7 M) images. However, for objects that do not contain high geometric detail, high pixel density is not required, and therefore acceptable results can be attained with cheaper cameras (Paixão *et al.*, 2018).

In order to investigate the effect of shooting distance on mesh quality, object 9 was modeled with photos taken from 30 cm and 120 cm distances. The number of faces and vertices number of the obtained model decrease as increasing distance. As the shooting distance increases, the area covered by the object in the picture frame decreases. Therefore, the number of faces and vertices of the model generated is inversely proportional to the shooting distance. In the 3D model obtained with pictures taken from a distance of 30 cm, the number of vertices of the object was determined as 145732 and the number of faces as 267696. The shooting distance was 120 cm, the number of vertices was 62790 and the number of faces was 113950. The software uses each pixel in the picture and converts them to faces and vertices. Therefore, we can conclude that filling the frame with the object while taking pictures provides high-mesh quality models. Fig. 11 shows variations in the number of faces and vertices according to the resolution and shooting distance.

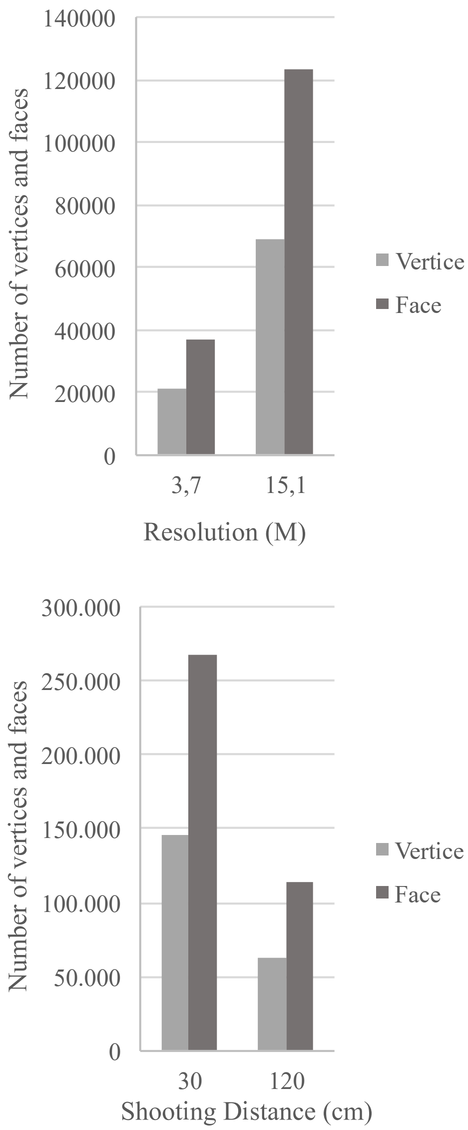

Fig. 11. *Variations in the number of faces and vertices according to the resolution and shooting distance.*

It is also possible to observe the change of the mesh structure depending on the resolution and shooting distance in the 3D mesh models of the generated models. It is seen that the mesh density proportionally increases when the resolution increases from 3.7 M to 15.1 M. However, the shooting distance affects the mesh density inversely (Fig. 12).

Finally, the effect of the number of images on mesh quality was investigated. Two models were generated by taking 24 and 48 photos of object 9. It was observed that the number of faces and vertices was almost the same for both models. Increasing the number of photos for the same object did not make a significant contribution to improving the mesh quality. Therefore, taking too many pictures of objects that do not have detailed geometry might be a waste of time.

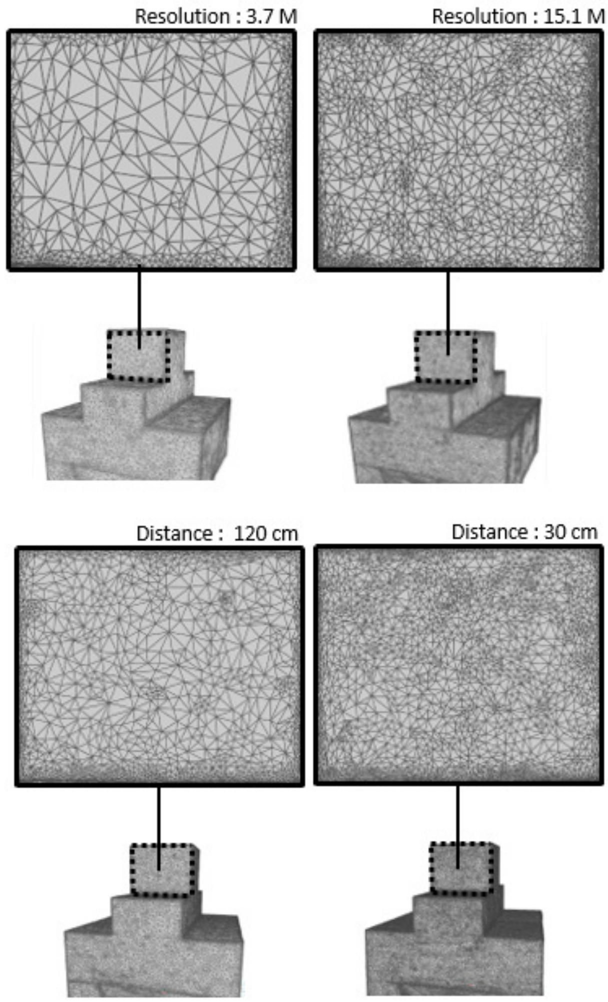

Fig. 12. *Variations in the mesh density according to the resolution and shooting distance.*

CONCLUSION

3D photogrammetry is a method that is being considered as an alternative to expensive 3D scanning methods by people from different disciplines working on a wide variety of materials and objects. Since the aim of this study is a fair evaluation of reconstructions of many different parameters under the same conditions with the same methods and equipment and to provide a general perspective for researchers working on 3D photogrammetry, many samples with different textures and geometric properties were reconstructed. The variety and number of samples limited detailed geometric analysis. A total of 48 solid and textured models generated from 24 plastic, wood, metal, glass, clay, fabric and organic objects with various geometries are presented in the paper. The effects of object texture, shape, environmental conditions, shooting angle and distance on the generation of the model are tried to be revealed. As a result of the 3D reconstruction applications, the following conclusions have been reached:

• 3D models of especially fabrics, organic and clay objects with highly featured textures were generated with high geometric and visual accuracy.
• Color differences in the textures of the objects may cause very thin layers to form on the surfaces. However, this effect can be used to improve geometric accuracy. When the object was remodeled after drawing edges with a marker, it has been observed that a geometric improvement is achieved along these edges. Therefore, the surfaces adjacent to these edges could also be modeled more successfully.
• In modeling objects with very thin wall thickness, taking photographs at 30° instead of the right angle significantly increased the reconstruction success.
• 3D reconstruction of transparent objects does not seem possible without the coating process with 3D photogrammetry. Glossiness and shadow on the object may cause some surface problems. Shaded areas on the object are modeled as curved surfaces, glossy areas as wavy surfaces. Surfaces outside the photo angle are modeled as holes. Models can be improved by taking photos from different vertical shooting angles for shadowed areas and surfaces outside the photo angle.
• For glossy objects such as metal, better results can be obtained by adjusting the ISO value according to the object's light reflectance intensity.
• Surface coating with a matte material such as powder enables the 3D reconstruction of transparent objects and increases geometric accuracy for metal objects.
• Photo frequency does not directly affect the mesh quality. However, if it is possible to define new surfaces with photographs taken from different angles, increasing the photo frequency may improve the geometric accuracy of the model.
• The photo resolution directly affects the mesh quality of the model. Therefore, high-resolution photographs may generate objects with many geometric details more accurately.
• The more objects that fit in the photo frame, the more faces and corners the model has. Therefore, the shooting distance and image resolution directly affect the quality of the mesh. We can therefore recommend close-ups for more successful results.
• Controlling the light, shadows, background, and other environmental conditions during photography is critical to the success of the reconstruction. For this reason, we recommend shooting in a closed environment where the lighting intensity does not change and is isolated from external factors. In addition, the shooting method where the camera is fixed and the object rotates on its axis is also highly recommended. Because in this method, the light direction and the background are fixed and there are no surprise shadows. In addition, the use of dark-colored, blank fabric that does not reflect light for the floor and background in photoshoots made a positive contribution.

Since the ability to obtain textured 3D models with photogrammetry is an important advantage, the method is useful in areas such as archeology, architecture, forensics, film and game production, where photo-realistic documentation and modeling play a major role. However, photogrammetry is known to provide lower geometric accuracy than some other expensive 3D scanning methods. The results that improve the geometric accuracy obtained in this study, such as shooting at 30 degrees for thin objects, adjusting the ISO value for objects with glossy surfaces, and drawing lines that define the edges of objects better, can be examined separately in future studies.

Many image-based 3D modeling software on the market offers various services. Software with cloud services such as ReCap Photo used in this study provides 3D reconstruction with low-equipped computers. Although 3D scanning and photogrammetry software has made significant progress in recent years, they are still insufficient in some basic issues. The development of 3D photogrammetry software for the 3D reconstruction of featureless surfaced and transparent objects without additional applications such as surface coating would be a major step forward in this area. Another issue is that the 3D reconstruction process cannot be completed correctly after moving or reversing the object. Developing a 3D photogrammetry software that can detect the direction and position changes of objects from the image data and use all the photographs taken before or after these changes in the same modeling operation may prevent a significant waste of time and effort.

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