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Convergence Modeling and Reproduction of a Bigyeokjincheolloe (Bomb Shell) Based on Three-dimensional Scanning and γ-ray Radiography

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ABSTRACT The Bigyeokjincheolloe (bomb shell), a scientific cultural heritage, has outstanding historical value for sustaining a gunpowder weapon of Joseon. In this study, the bomb shell was modeled through three-dimensional (3D) scanning centered on the external shape and γ-ray radiography-based on the internal shape. In particular, to improve the contrast in the radiographic image, optimization and image processing were performed. After these processes, the thickness of the inner wall (2.5 cm on average) and the positions of the three mold chaplets were clearly revealed. For exhibition purposes, the 3D model of the bomb shell was output to a 3D printer and the output was rendered realistic by coloring. In addition, the internal functional elements, such as Mokgok, fuse, mud, gunpowder, and caltrops, were reproduced through handwork. The results will contribute to the study of digital heritages in two ways. First, the internal and external shapes of the bomb shell were modeled by fusing two different technologies, namely, 3D scanning and γ-ray radiography. Second, the internal shape of the bomb shell was constructed from the original form data and the reproduction was utilized for museum exhibitions. The developed modeling approach will greatly expand the scope of museum exhibitions, from those centered on historical content to those centered on scientific content.

Key Words Three-dimensional scanning, γ-ray radiography, Bigyeokjincheolloe (bomb shell), Convergence modeling, Reproduction

1. INTRODUCTION

The Bigyeokjincheolloe (bomb shell) is a gunpowder weapon with the Jungwangu (medium mortars) used in the Japanese invasion of Korea in 1592 (Lim, 2019; Huh and Kim, 2020). It is said to have been invented by Jang-son Lee in the 24th year of King Seonjo (1591) in the Joseon Dynasty. The Bigyeokjincheolloe is spherical in shape and constructed from cast iron. Characteristically, the bomb shell is a time bomb that explodes after flying to the target point when fired from a cannon called Wangu. The inside of the bomb shell is filled with gunpowder and caltrops, and is inserted a bamboo tube and Mokgok (corrugated wood) with a fuse wound around it. The explosion time can be adjusted by changing the number of fuse windings around the Mokgok (Lim, 2019). According to historical records, the bomb shell exerted great power in various battles, such as the fight to recapture Gyeongjuseong (1592), the Battle of Jinju (1592), the Battle of Haengjusanseong (1593), and the Battle of Namwonseong (1597).

Six bomb shells have been identified in the Republic of Korea, including the bomb shell owned by the National Palace Museum of Korea. A further 11 pieces were excavated in the eight excavation survey of the Mujang-hyeon

Government Office and Town Wall carried out in 2018, increasing the number of known bomb shells to 17. The bomb shells excavated from Mujangeupseong Town Wall were relatively sound and have contributed greatly to historical studies. To conserve the original forms, conservators of the Jinju National Museum carried out scientific investigations and treatments.

Previous studies on the bomb shells have mainly considered their time of introduction (Lim, 2019), function as a weapon (Yoon, 2019), and manufacturing technique and conservation treatment (Kim and Huh, 2020). Morphological reproduction for understanding the scientific principles of bomb shells is rarely reported. In addition, even when the internal shapes of artifacts are important (as in the case of bomb shells), most studies model only the surface shapes from three-dimensional (3D) scanning results (Karasik and Smilansky, 2008; Younan and Treadaway, 2015). When the internal structure is required, it is generally estimated based on historical data (Lee *et al.*, 2011). However, various non-destructive testings have recently been performed alongside 3D scanning of single artifacts, laying the foundation for restoration and reproduction of the original forms (Jo *et al.*, 2019; Bossema *et al.*, 2021; Rankin *et al.*, 2021).

In this study, basic data on the internal and external shapes of the bomb shell were collected by simultaneous 3D scanning centered on the surface shapes and γ-ray radiography centered on the internal shape. Based on the results, reproductions for museum exhibitions were prepared by 3D modeling, printing, and coloring. Through these reproductions, audiences can understand the morphological manufacturing technique and scientific principles of the bomb shell.

2. THREE-DIMENSIONAL SCANNING AND SHAPE ANALYSIS

The studied bomb shell was excavated from Mujangeupseong Town Wall in Gochang and weighed 16.3 kg. Corrosions and irregularities appear over the entire surface, and the interior contains various shape information that reveals the manufacturing technique (Figure 1). First, the surface shape of the bomb shell was recorded in 3D by fixed-type high-precision scanning (HDI Advance R3X, LMI Technologies, CAN). This technology is essential for digital documentation of cultural heritages and is variously applied to buildings, artifacts, and natural heritages (Park *et al.*, 2019. Alshawabkeh *et al.*, 2020; Jung *et al.*, 2021). Recently, it has become recognized as a key technology for digital solutions such as optimized modeling, visualization, shape analysis, diagnosis, restoration, reproduction, and content of cultural heritages (Angelo *et al.*, 2018; Dostal and Yamfune, 2018; Jo and Hong, 2019a; Kim *et al.*, 2019; Moyano *et al.*, 2020; Choi *et al.*, 2021; Jo *et al.*, 2021; Wilczek *et al.*, 2021).

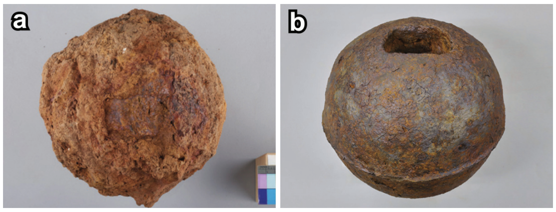

Figure 1. The Bigyeokjincheolloe (bomb shell). Before (a) and after (b) Conservation treatments.

In this study, white structured light was projected onto the bomb shell and the precise numerical data and RGB color values were obtained from the reflection and interference phenomena occurring on the surface. For on-site 3D scan, two lens with a 12-mm focal lengh was set to a distance of 200 mm, and the bomb shell was scanned 124 times with an accuracy of 40 μm. The scanned images were sequentially processed (Geomagic Design X 2019, 3D Systems, USA) by noise filtering, registering, merging, and texture mapping (Figure 2). The partial reflection effects on the conservation-treated bomb shell, which degrade the quality of the polygons, were removed prior to registering each scan model.

After 3D scanning of the bomb shell, the model was composed of 6,271,151 point clouds and 12,537,276 polyfaces, and showed high resolution with an average point density of 0.15 mm. From this 3D model, the external dimensions of the bomb shell were measured. The horizontal and vertical diameters were very similar (19.5 cm and 18.1 cm, respectively). The beak part, the entrance through which the fuse-wound Mokgok tube is inserted into the bomb shell, is rectangular with a width and length of 4.5 cm and 6.7 cm, respectively (Figure 3). The path of the Mokgok is 14.4 cm in diameter, and the gunpowder hole located at the center of

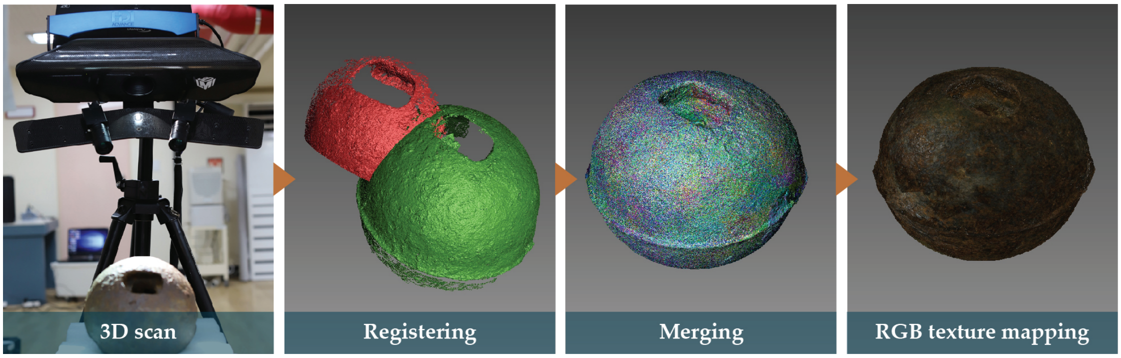

Figure 2. On-site 3D scan and data processing.

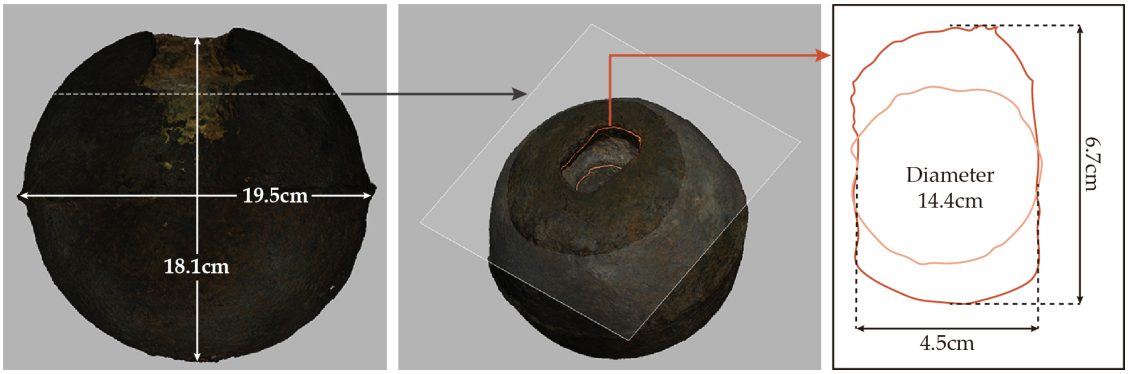

Figure 3. Measurements of the external dimensions and beak part of the bomb shell.

the side of the bomb shell is 1.4 cm in diameter.

3. γ-RAY RADIOGRAPHY AND IMAGE ANALYSIS

3D scanning technology cannot easily identify the internal structure of the bomb shell, which is hidden from the naked eye. To understand the internal structure of the bomb shell, radiographic imaging using X-rays or γ-rays is required. X-rays have been widely used in traditional internal investigations of cultural heritages and analyses of manufacturing techniques (Han *et al.*, 2014; Lee *et al.*, 2021; Song and Kim, 2021). More recently, radiographic imaging has been expanded to computed tomography technology, enabling multifaceted analyses (Hoffman *et al.*, 2002; Machado *et al.*, 2019; Park and Yang, 2020; Na and Hwang, 2021). Meanwhile, as γ-rays have shorter wavelengths and stronger penetrating power than X-rays, they can non- destructively probe artifacts that cannot be penetrated by X-rays (Han *et al.*, 2012; Lee *et al.*, 2013; Yi *et al.*, 2013).

The externally closed structure of the bomb shell prevents an understanding of the internal structure through visual observation and 3D scanning. In addition, the internal structure is dense and thick, and the penetrating power of X-rays is insufficient for determining the thickness and manufacturing technique. Therefore, the bomb shell was penetrated by γ-rays emitted from a Co-60 radiation source (Figure 4a).

Although γ-ray radiography revealed the approximate thickness and internal structure of the bomb shell, the contrast was nonobvious in areas of weak penetrating power (Figure 4b). Therefore, the contrast in these areas was first optimized using image processing software (PicMan, WaferMasters, USA) (Figure 4c). Thereafter, the color information in the pixels of the two-dimensional (2D) image was processed to emphasize the relief effect and critical points (Figure 4d, 4e). After these image processing steps, the overall shape of the

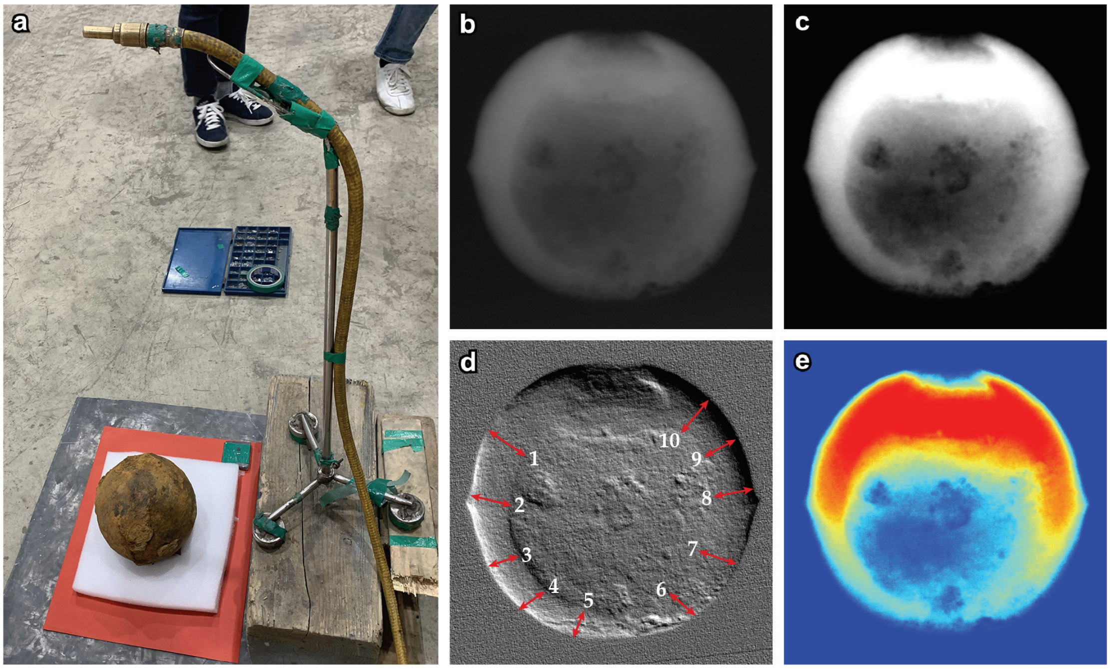

Figure 4. γ-ray radiography and image processing of the bomb shell. (a) γ-ray radiography using a Co-60 radiation source. (b) The original image acquired from the γ-ray radiography. (c) The optimized image to visualize the internal structure of the bomb shell. Relief effect (d) and critical points mapping (e) through the image processing.

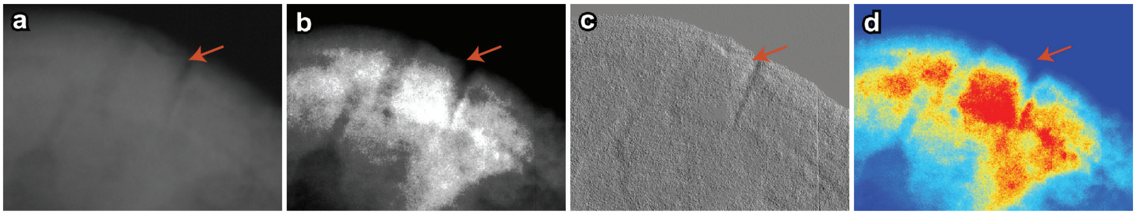

Figure 5. Image processing of the chaplet. (a) The original radiography image. (b) Optimized radiography image. (c) Relief effect. (d) Critical points mapping.

internal structure of the bomb shell was much clearer than in the original radiographic image.

Next, the thicknesses of 10 points were measured based on the image processing results. The internal thickness of the bomb shell was nonuniform and ranged from 2.2 to 3.0 cm. The beak (entrance for inserting the gunpowder and Mokgok) was the thickest part of the structure while the lower part and sides were relatively thin. The chaplet maintains the distance between the inner and outer molds during casting. Three equally spaced chaplets were found in the γ-ray radiography data (Figure 5). The inner-wall thickness information and the chaplets provided important basic data for the 3D modeling.

4. THREE-DIMENSIONAL MODELING AND REPRODUCTION

The external-surface shape of the bomb shell was precisely recorded through 3D scanning and the internal structure was identified by γ-ray radiography. The 3D-scanned models and γ-ray radiographic images were used as the basic data for creating a 3D convergence model of the bomb shell. The 3D modeling was intuitively performed in voxel software (Geomagic Freeform Plus, 3D Systems, USA) through a haptic device (Geomagic Touch X, 3D Systems, USA). This system is widely used in digital virtual restorations of cultural heritages (Jo *et al.*, 2020c; Shin and

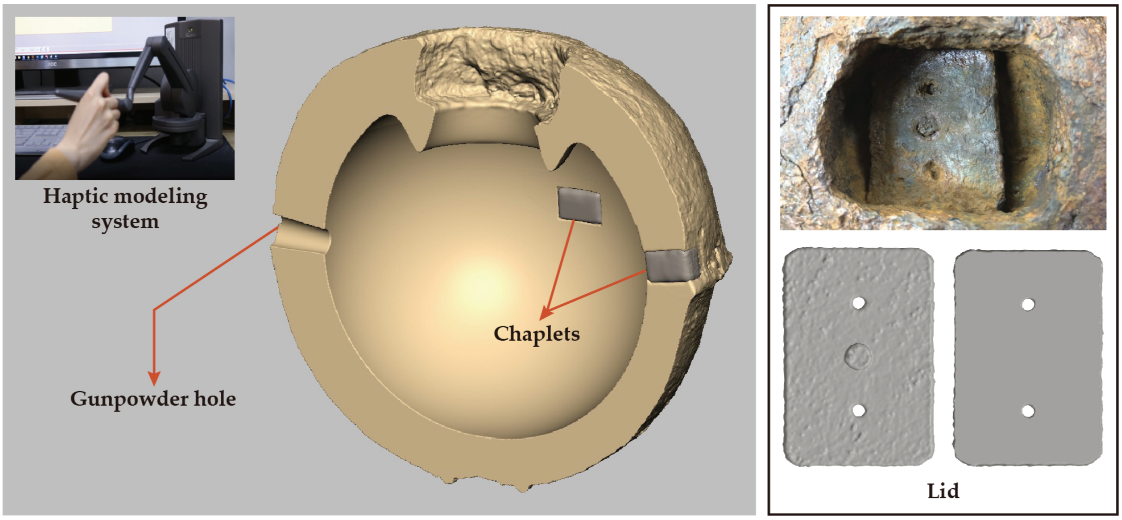

Figure 6. The 3D modeling of the bomb shell based on the 3D-scanned models and γ-ray radiographic images.

Wi, 2020; Jo and Lee, 2021).

The 3D modeling of the bomb shell was sequentially performed by external shape modeling, reflection on the inner-wall thickness, and modeling of the functional structural elements (Figure 6). The external shape was assumed as the 3D scanning model and the inner-wall thickness was taken as the average thickness of 2.5 cm (2.2—3.0 cm) identified by γ-ray radiography and image processing. Finally, the structural elements (chaplet, lid, and gunpowder hole) were modeled based on historical evidence data and condition investigation (Kim and Huh, 2020).

Among the structural elements, the chaplets' 3D shape was difficult to discern in the 2D γ-ray images, and the three chaplets are not standardized. Therefore, they were modeled as rectangular objects of sizes and their locations were considered a hemispherical shape of reproduction. In addition, the lid was modeled using the numerical data recorded in the condition investigation and its size alone was adjusted to fit the studied bomb shell (Kim and Huh, 2020). However, the modeled lid is required additional review because it is slightly different in shape compared to the lid recorded ancient document (Yungwonpilbi). The gunpowder hole was made by penetrating the inner wall from the outside based on the diameter measured in the 3D scanning model.

To utilize the 3D model of the bomb shell in exhibitions, reproductions should be manufactured. Such reproductions are traditionally constructed manually, but are now being formed by 3D printing technology, which can be linked with scanning and modeling to produce real reproductions in one step (Lee and Wi, 2015; Balletti *et al.*, 2017; Jo and Hong,

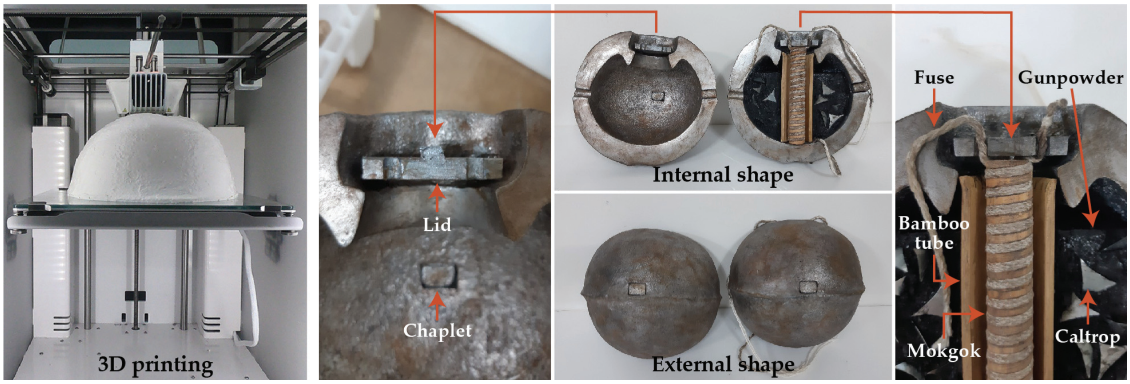

Figure 7. 3D printing of the digital model and reproduction of the bomb shell.

2019b; Jo *et al.*, 2020a; Lim and Choi, 2020; Higueras *et al.*, 2021). In this study, the modeling results of the bomb shell were output to the 3D printing technology using the material extrusion method (Ultimaker 3 Extended, Ultimaker B.V., NLD). The output material was polylactic acid filaments and the additive thickness was set to 0.15 mm. The realism of the 3D printed output was enhanced by coloring. The Mokgok + fuse, mud + gunpowder, and caltrops were reproduced by hand (Figure 7).

5. DISCUSSION

The bomb shell, a gunpowder weapon of Joseon, was reproduced through 3D modeling and subsequent 3D printing. The results will contribute to the study of digital heritages in two ways. First, the internal and external shapes of the bomb shell were modeled by fusing two different technologies, namely, 3D scanning and γ-ray radiography. Convergence modeling using terrestrial laser scanning + unmanned aerial photogrammetry and optical surface scanning + X-ray computed tomography has already been reported in many studies (Fawzy, 2019; Lee, 2019; Jo *et al.*, 2020b; Shimizu *et al.*, 2022).

However, the fused technologies in these studies were based on 3D data so the modeling was straightforwardly based on the original form. In contrast, the 3D modeling of the bomb shell used the shapes in 2D images extracted by γ-ray radiography, and the internal shapes were inferred through image analysis in numerical value-based modeling (Figure 8). This method was optimal for modeling the bomb shell, which is not easily penetrated by X-rays.

Second, the internal shape of the bomb shell was constructed from the original form data and the reproduction was utilized for museum exhibitions. In general, digital documentation of the artifacts is sufficient for obtaining surface information through 3D scanning. However, when the scientific principles and functions of the artifact are also important (as in the case of the bomb shell), showing the internal structure and functions will increase the value of the exhibit and enhance the audiences' understanding of the artifact. In this study, an optimal exhibit that shows the functional elements of the artifact was produced through a sequence of 3D scanning, γ-ray radiography-based modeling, 3D printing, and coloring. This processing sequence is expected to expand museum exhibitions from a focus on historical content to a focus on scientific content (Figure 9).

Artifacts formed by digital convergence modeling and their utilization in museum exhibitions will be crucial for future digital heritage research. However, the two-dimensional image and three-dimensional model fundamentally have a different morphological structure. Accordingly, the image processing and optimizing are required prior to integrating the image and model. Various digital technologies are being rapidly developed and actively applied to cultural heritages, resulting in many digital datasets. As accessing and utilizing these materials can preserve digital heritages, increasing the usability of already established or newly constructed digital materials is expected to become a research focus.

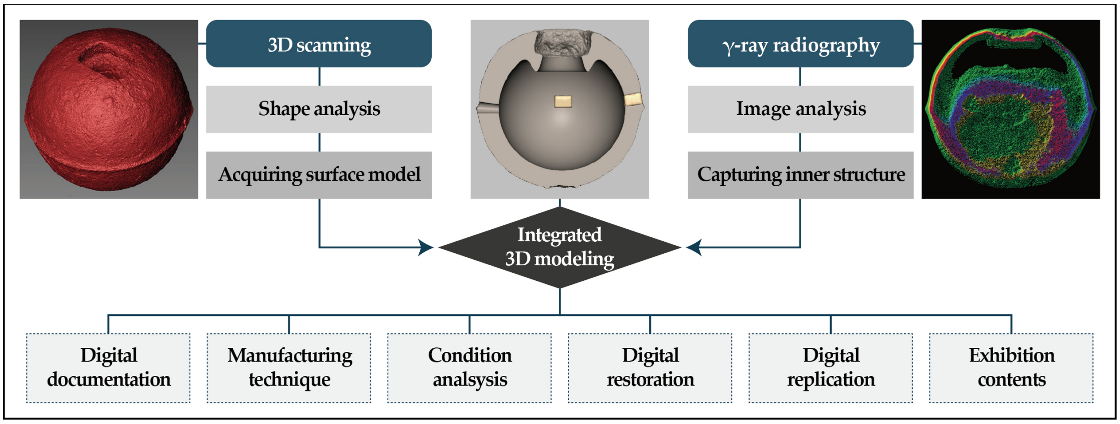

Figure 8. Methodology suggestions of integrated 3D modeling based on the 3D scanning and γ-ray radiography.

Figure 9. Exhibition utilization of the bomb shell reproductions in Jinju national museum.

6. CONCLUSION

The bomb shell, a scientific cultural heritage, has outstanding historical value for sustaining a gunpowder weapon of Joseon. In this study, the bomb shell was modeled through 3D scanning centered on the external shape and γ-ray radiography-based on the internal shape. The result was then 3D-printed and colored to form a reproduction. The 3D scanning model was generated with high resolution (average point density = 0.15 mm) and provided information on the horizontal (19.5 cm) and vertical (18.1 cm) diameters of the bomb shell, the size of the beak (4.5 cm in width, 6.7 cm in length), the Mokgok passage (14.4 cm), and the gunpowder hole (1.4 cm).

The 3D scanning established precise information on the external shape and dimensions of the bomb shell but did not provide the geometrical data of the internal structure. Instead, the internal structure of the bomb shell was understood through γ-ray radiography. To improve the contrast in the radiographic image, optimization and image processing were performed. After these processes, the thickness of the inner wall (2.5 cm on average) and the positions of the three mold chaplets were clearly revealed.

The 3D scanning models and γ-ray radiographic images became the basic data for modeling the internal and external shapes of the bomb shell. Referring to historical evidences and condition investigation, the external appearance, inner-wall thickness, and functional structural elements of the bomb shell were then reflected on the modeling to complete the digital restoration. For exhibition purposes, the 3D model of the bomb shell was output to a 3D printer using the material extrusion method and the output was rendered realistic by coloring. In addition, the internal functional elements (Mokgok + fuse, mud + gunpowder, and caltrops) were reproduced through handwork.

The above results contribute to digital heritage studies in two ways. First, the internal and external shapes of the bomb shell were modeled by fusing 3D scanning with γ-ray radiography. In particular, γ-ray radiography is optimal for probing bomb shells, whose dense internal materials are not easily penetrated by X-rays. Second, an optimal exhibit showing the functional elements of the artifact was reproduced from the original data of the internal shape of the bomb shell. The developed modeling approach will greatly expand the scope of museum exhibitions, from those centered on historical content to scientific content.

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