The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-M-2-2023
29th CIPA Symposium "Documenting, Understanding, Preserving Cultural Heritage:
Humanities and Digital Technologies for Shaping the Future", 25–30 June 2023, Florence, Italy

A STUDY ON CONVERGENCE MODELING OF CULTURAL ARTIFACT USING X-RAY COMPUTED TOMOGRAPHY AND THREE-DIMENSIONAL SCANNING TECHNOLOGIES

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KEY WORDS: X-ray Computed Tomography, Three-dimensional Scanning, Convergence Modeling, Cultural Artifact

ABSTRACT:

Optical three-dimensional (3D) scanning technology is extensively used for digital recording and shape analysis of cultural heritage because it is simple to obtain precise surface shape and color information. In addition, X-ray computed tomography (X-ray CT) is used to record and analyze the internal shape of cultural heritage. However, while the 3D shape acquired by X-ray CT technology is excellent for visualizing the internal shape, expressing the high resolution of the surface shape is difficult. If the benefits of each technology are used to digitize the inside and outside of cultural heritage, the results of surface shape recording based on 3D scanning can be advanced, and various stereoscopic analysis can be performed. Therefore, an optimization modeling process that combines X-ray CT and optical surface scanning is required to record both internal and external shapes of cultural heritage. In this study, optimization modeling methodology was applied to cultural heritage by combining X-ray CT technology and optical 3D scanning technology. Based on the models obtained through both technologies, a mesh-based optimization convergence modeling methodology considering internal and external surface shapes and color is organized. Furthermore, because the X-ray CT data has a characteristic of a voxel base, it is determined that additional convergence methods, including internal voxel data, are required, and a voxel-based optimization model process is established concurrently. Following that, two convergence modeling methods were applied to each of the deer-shaped horn cup artifacts that had an interior shape. As a result, the 3D convergence model creation and mapping optimization process, which can reveal important internal and external information about artifacts such as surface color, fine shape, and internal structure, can be improved. This 3D convergence modeling methodology was able to supplement the two technologies while preserving the benefits of optical 3D scanning and X-ray CT technology. This is thought to contribute to the expansion of the digital recording process from a single technology to multiple technologies. The X-ray CT-based convergence modeling pipeline is expected to be an opportunity in promoting the revitalization of X-ray CT technology in the cultural heritage field because it can be used for a wide range of purposes such as shape analysis, preservation status evaluation, monitoring, restoration, and reproduction.

1. INTRODUCTION

Presently, the three-dimensional (3D) scanning method is used to construct a digital database of the original forms of cultural heritage internationally (Al-Baghdadi, 2017; Lv et al., 2020; Gautier et al., 2020; Kesik et al., 2022; Hutson et al., 2023). Although the 3D scanning technology has the advantage of capturing precise surface numerical information of cultural heritage, it is difficult to depict the overall internal and external structure of cultural heritage that has various manufacturing techniques and preservation conditions (Jo et al., 2019; Kim, 2021). Therefore, if shape analyses and interpretations are required, additional data acquisition through other techniques is required for convergence.

Particularly when internal shape data of artifacts is required, additional data acquisition techniques are necessary because surface-centric optical scanning alone is insufficient to capture such data. A typical method is transmission imaging using radiation. However, given that radiographic results present 3D shapes as fragmentary 2D results only, the image analysis and modeling of artifacts with complex or diverse layered features inside is limited (Song et al., 2018; Song and Kim, 2019).

To overcome this issue, X-ray computed tomography (CT) is actively used for the scientific investigation of artifacts. X-ray CT reveals new physical information that is not identified in non-destructive testing using ultraviolet, infrared, and terahertz radiations and can be used for the analysis, diagnosis, and restoration of artifacts (Brancaccio et al., 2011; Albertin et al., 2019; Fauzia et al., 2022). However, although X-ray CT is an excellent technique for obtaining the non-visible information inside artifacts, it lacks high surface precision and resolution compared to 3D scanning models because it is computerized using tomographic images.

Further, both optical 3D scanning and X-ray CT have different advantages and can be applied as hybrids due to their high digital flexibility for convergence. If the interior and exterior of cultural heritage can be digitized by utilizing the advantages of each technology, various 3D analyses and the results of surface shape recording centered on existing 3D scanning can be enhanced. Therefore, an optimization modeling process that can fuse X-ray CT and 3D surface scanning must be developed to record the internal and external shapes of artifacts.

Herein, the study of optimization modeling methodology that can be applied to cultural heritage was conducted by fusing X-ray CT and optical 3D scanning technologies. Based on the model obtained through the two technologies, the mesh and color information optimization convergence modeling methodology, which considers the inner and outer surface shapes and colors, was organized.

Additionally, since X-ray CT data is voxel-based, an additional convergence method that includes internal voxel data was necessary. Therefore, the voxel and color information optimization model processes were established simultaneously. Finally, the modeling process was systematically established by directly applying the convergence methodology of the two technologies to artifacts, and a method suitable for recording and preserving cultural heritage was proposed.

2. MATERIAL AND METHODS

The deer-shaped pottery horn cup excavated from ancient tombs in Marisan Mountain, Haman, which underwent X-ray CT-based convergence modeling, is 17cm long and 20 cm high and is believed to have been produced in the 5th to 6th centuries. Physically, it is an Ara Gaya-era earthenware horn cup that embodies the moment a deer-shaped animal that glances back. The deer-shaped body is placed on a conical handle, and a U-shaped cup is attached to the center of the back of the body to show excellent formability. Furthermore, Ara Gaya's unique flame-shaped holes are depicted on the lower leg of support body, which exhibits a unique earthenware production technology.

This study used optical 3D scanning and X-ray CT data, which were archived the Cultural Heritage Conservation Science Center of the National Institute of Cultural Heritage (Figure 1). The X-ray CT voxel model has the advantage of obtaining the information of the artifact's interior, enabling visualization and quantitative measurement. However, since it relies on the transmission characteristics of X-ray radiation, the surface accuracy is poor, and it is difficult to express the color of the artifact. Therefore, based on the internal information of artifacts in voxel models, a methodology that fuses precise surface shape and color information from the scanned data.

Herein, image processing and 3D modeling of the X-ray CT data were conducted using VGSTUDIO MAX software from Volume Graphics. This software has a multiplanar reformatting window and a 3D volume rendering window that allows the viewing of 2D images simultaneously. Therefore, the CT model can be visually verified, and the mesh model can be extracted by specifying the surface determination in detail.

Given that optical 3D scanning and X-ray CT use different scanning methods and light sources, RMS deviation analysis for mutual consistency verification must be preceded to apply the convergence modeling methodology. It is necessary to analyze the shape difference between the two scanning results and numerically verify whether the error is large when the results match. The 3D Systems' Geometric Control X software was used for deviation analysis. The software visualizes complex numerical data by analyzing deviations from variations in the mesh model.

3. MESH-BASED CONVERGENCE MODELING

The mesh model built with optical 3D scanning was mapped with a precise polygon with an average point distance of 0.08 mm and an RGB color. Additionally, the X-ray CT model included voxel data with 3D reconstruction, revealing that cylindrical horn cups, upper body, lower body, and legs were individually manufactured and bonded. The deer head was connected to the lower part of the body, and traces of a separate cover were observed on it. The surface was trimmed, and the traces of hand-pressing existed inside the pottery wall to increase the soil adhesion (Figure 2). Additionally, the head and neck were filled with soil, and a space that can filled with liquid was observed inside the cylindrical horn cup and its connected body.

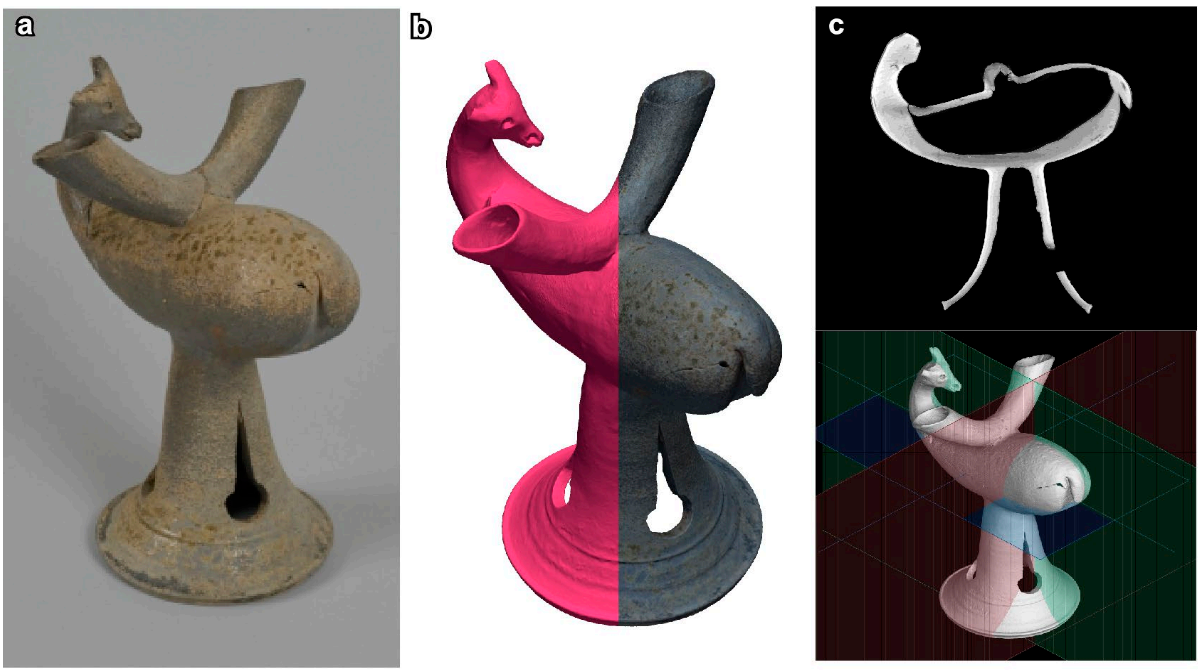

Figure 1. Deer-shaped pottery horn cup excavated from ancient tombs in Marisan Mountain, Haman. (a) Digital photo. (b) 3D scanning model. (c) X-ray CT model.

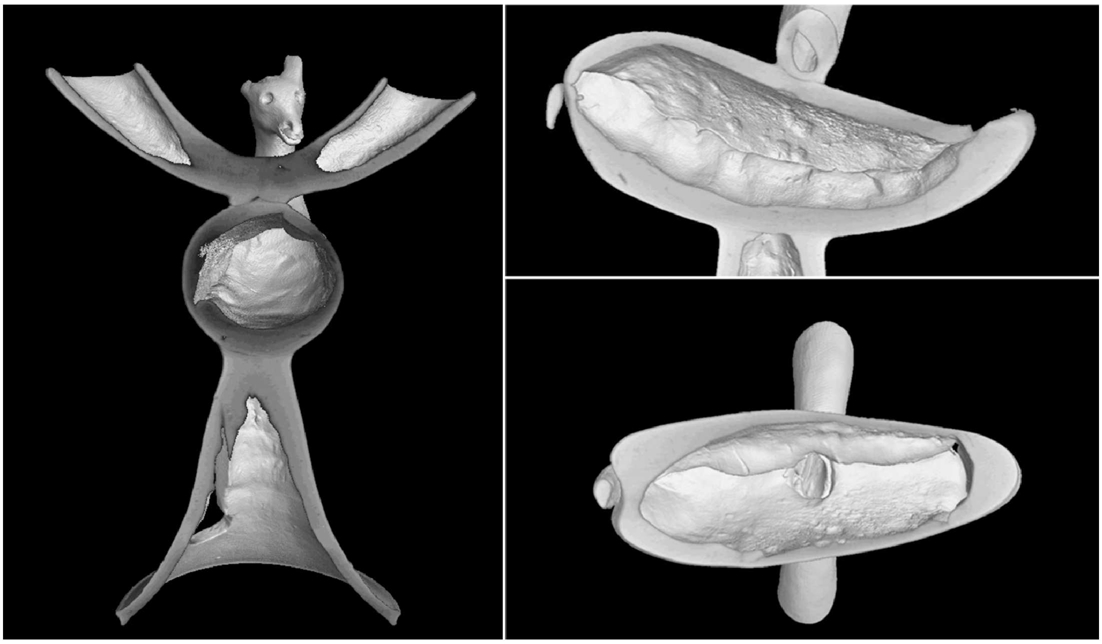

Figure 2. X-ray CT model of the deer-shaped pottery horn cup.

It is believed that these five shapes can be separated through image processing because their boundaries are clearly defined by differences in density. However, as the X-ray CT model was reconstructed into a 3D shape using tomographic images, the surface precision and resolution were low. Therefore, convergence modeling by creating a single 3D model that combines an internal mesh model obtained through CT with an external surface mesh model and color information obtained through optical scanning.

First, the 3D voxel model obtained by X-ray CT was image-processed and converted into a mesh model. To this end, a surface threshold that sets the boundary between the target artifact and the air layer was designated. Surface determination is unable to precisely specify when unevenness, noise, and scattering of the target surface are severe or when the density difference between the air layer and the material is small. After precisely capturing the surface determination as much as possible at the density boundary, it was then converted into a mesh based on this boundary. The converted mesh data was completed into a final 3D mesh model through a defect optimization process.

The two mesh models of 3D scanning and X-ray CT were then placed in the same coordinate through a feature alignment process. Although the overlapping regions of the two models did not perfectly match, they placed almost the same geometric information. Thereafter, to inspect the mutual consistency of the two mesh models, deviation analysis was performed using 3D scan data with the X-ray CT model as the reference. The shape accuracy was 64.5% within the specified ±0.4 mm tolerance range based on the resolution of the CT mesh model, and both the standard deviation and RMS showed 0.5 mm.

Shape alignment and consistency inspection determined that the deviation was small, and the fusion process of the two models was conducted. For an X-ray CT mesh-based optimization convergence model, the overlapping regions of the two aligned mesh models were removed. The X-ray CT mesh model’s external surface mesh is not as precise as 3D scanning model. Therefore, when combined with the 3D scanning model in the convergence modeling process, it results in a degraded surface. Therefore, to preserve the excellent external surface and shape of the 3D scanning model, we removed the external shape of the CT mesh model, leaving only the internal shape. This was done to minimize data interference between the two models.

Thereafter, the 3D scanning external mesh model and X-ray CT internal mesh model were merged and converted into one mesh model. Lastly, the final convergence model was completed by removing the noise generated in the finely overlapped region and mapping RGB color.

4. VOXEL-BASED CONVERGENCE MODELING

The second method of 3D convergence modeling was an optimized convergence modeling method based on a voxel model of X-ray CT. This methodology fuses the color information of artifact while maintaining 3D voxel information that has undergone a reconstruction process. First, the surface threshold of the X-ray CT voxel was set for boundary. This boundary was transformed into a mesh to optimize the color on the surface of the voxel model.

Mapping the RGB color of optical surface scanning to X-ray CT mesh models was processed in a mesh optimization software. Afterward the CT mesh model, to which the color was mapped, was aligned with the voxel model in the CT software, where the voxel model could be viewed. In this way, a voxel-based optimization model that includes the information on the fault of the artifact and can express external color simultaneously was completed (Figure 3). The 3D convergence model of the deer-shaped horn cup complemented the limitations of each technique while maintaining the strengths of the optical 3D scanning model and the X-ray CT model. Additionally, it can record internal density information, thickness, and structure simultaneously while checking the precise surface shapes and colors of actual artifacts.

https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-851-2023

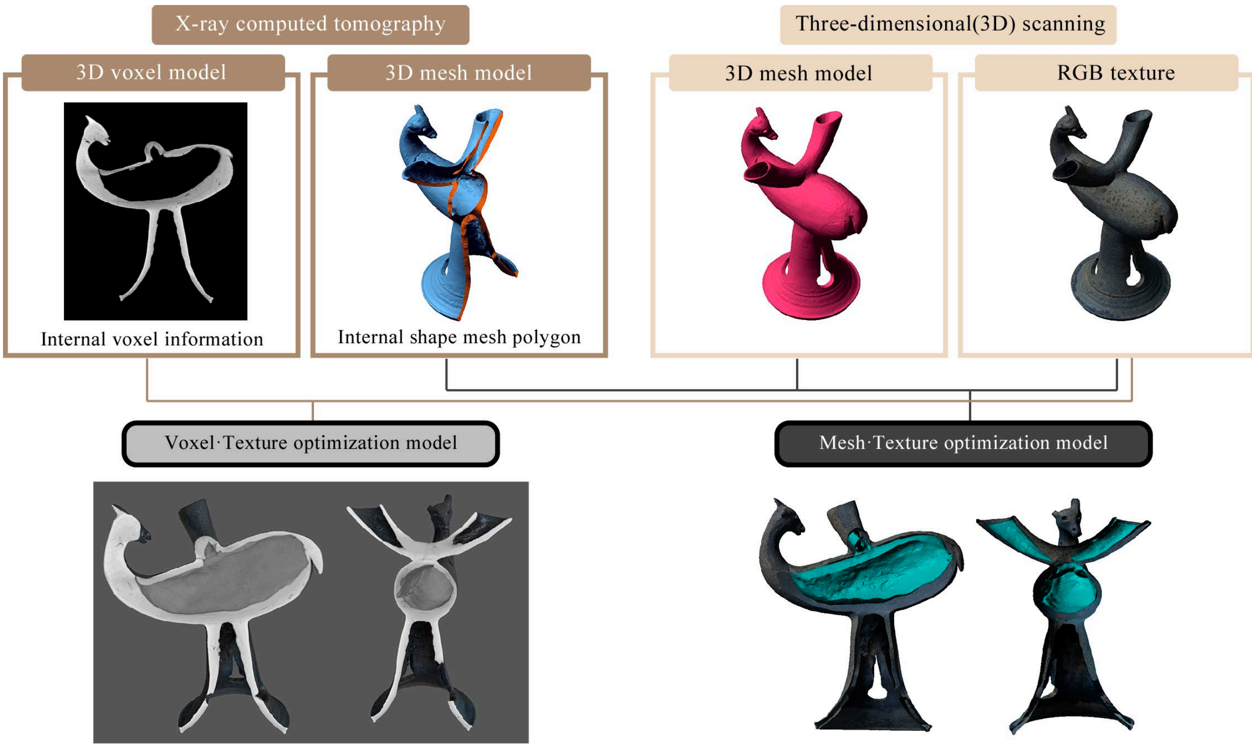

Figure 3. 3D convergence modeling results of the deer-shaped pottery horn cup.

5. DISCUSSION AND CONCLUSION

Herein, a study of an optimization modeling methodology that can be applied to cultural heritage artifact was conducted by convergence X-ray CT and optical 3D scanning technologies. By fusing X-ray CT optimized for internal shape acquisition and optical surface scanning results optimized for surface shape acquisition, a convergence model that can analyze the internal and external structures of cultural heritage artifact in various ways was developed . A 3D convergence model was developed that can show elements of manufacturing techniques, such as surface color, fine shape, and interior structure. Particularly, a mesh-based and voxel-based color convergence optimization methodology was developed and applied to artifact(Figure 4).

In the case of mesh-based color optimization modeling, alignment and merging were carried out around based on the external shape of 3D scanning and the internal shape of X-ray CT, minimizing data processing interference caused by overlapping areas. Additionally, noise generated during merging was removed by optimizing defects, and RGB colors were mapped onto the scan data to complete the final convergence model.

Meanwhile, in the case of voxel-based color optimization modeling using the 3D scanning mesh model and the voxel model of X-ray CT, the UV textures of the scan data were mapped onto the X-ray CT mesh model, and this model was extracted in a compatible format with X-ray CT software. Then, the mesh model with RGB colors was aligned with the X-ray CT voxel model to complete the voxel and color optimization model, which allows for the confirmation of both voxel and color information together.

By establishing modeling standards that align with the intended purpose, integrating the internal and external shapes of cultural heritage, and optimizing color mapping, it is expected that the effectiveness of 3D convergence models of artifacts will be enhanced. In future, if the degree of scattering of X-ray CT images can be optimized, an improved X-ray CT model-based convergence model can be developed. Moreover, the deviation between the 3D models of different technologies can be reduced to improve the dimensional and shape accuracy.

This 3D convergence modeling methodology is effective in the complementary application of optical 3D scanning and X-ray CT technology. Further, this study is expected to contribute to the expansion of the digital recording process to multiple technologies, which is currently focused on a single technology. Additionally, the X-ray CT-based convergence modeling pipeline is expected to serve as a steppingstone for promoting the activation of X-ray CT technology in the cultural heritage field because it can be used for various purposes, such as shape analysis, preservation evaluation, monitoring, restoration, reproduction, and content production.

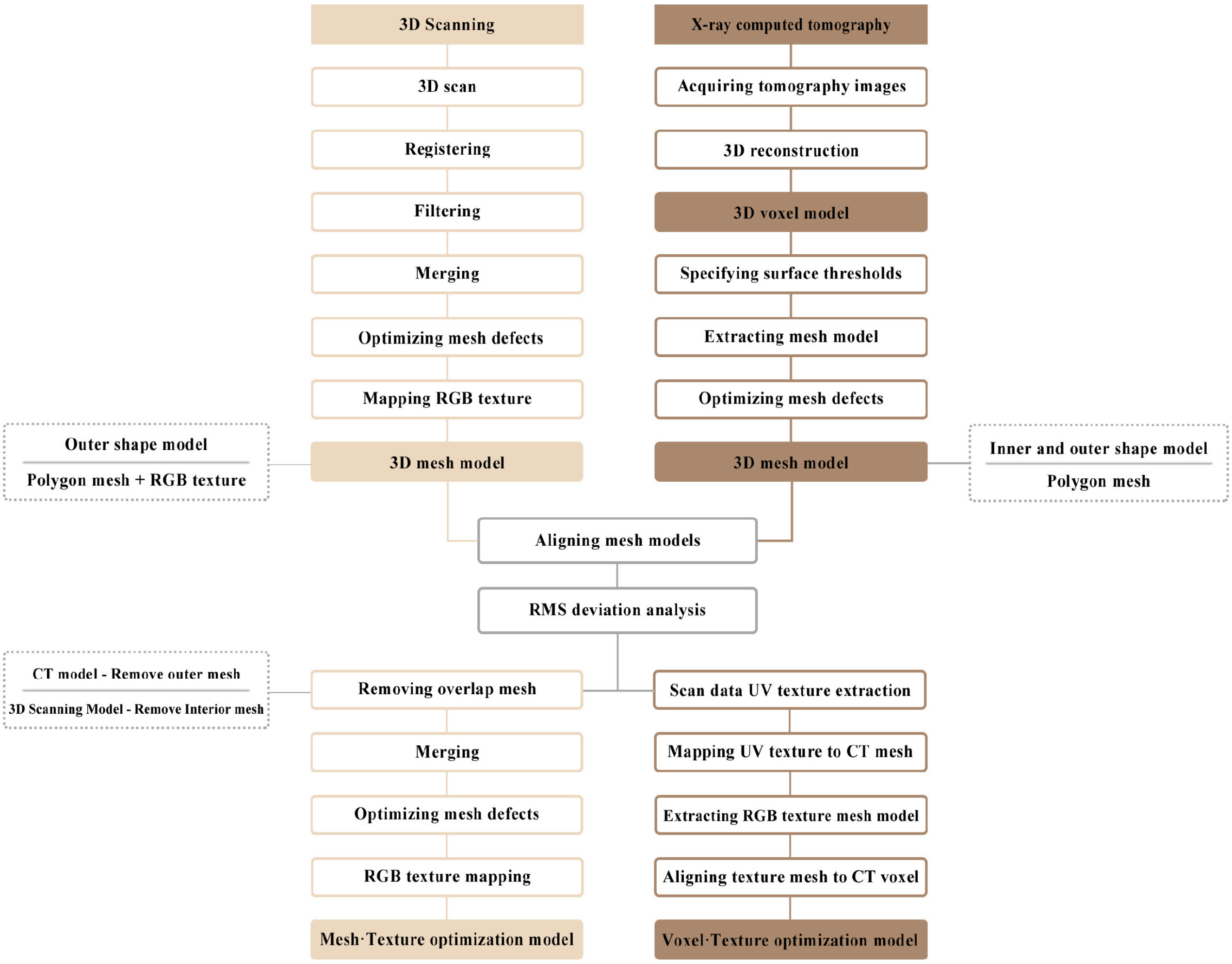

Figure 4. 3D convergence modeling process.

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