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# Spatial Representation Using Mixed Reality of Aluminum Die-cast Imaged by 3D X-ray Computed Tomography

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X-ray computed tomography (CT) is widely used as a nondestructive inspection technique in the medical, security, and industrial fields. The authors propose a method of visualizing the internal defect structure of an aluminum die-cast part imaged by 3D X-ray CT for industrial use using mixed reality (MR). In the proposed method, the data acquired by X-ray CT is reconstructed three-dimensionally using surface rendering and cross-sectional representation, and integrated into an MR environment using a spatial reality display and motion capture. The spatial reality display's eye-tracking function enables the provision of 3D images according to the user's viewpoint, and by using motion capture, it is possible to rotate and move objects using hand gestures, enabling intuitive interaction. As a result of the experiment, this system made it possible to intuitively understand the internal structure, which was difficult with conventional visualization methods using a fixed viewpoint. In addition, it became possible to understand the space more than with 2D visualization methods by segmenting and grasping defects and voids in three dimensions. The proposed visualization method using MR is expected to contribute to the nondestructive inspection of industrial products with complex shapes, such as automobile parts and precision equipment, in the future.

## 1. Introduction

X-ray computed tomography (CT) is widely used not only in medical diagnosis and security screening but also in nondestructive testing in the industrial field. In the industrial field, its usefulness is recognized in various applications, including detecting internal defects in products, quality control, dimensional measurement, failure analysis, and reverse engineering.

In recent years, the advent of direct conversion photon-counting X-ray CT using semiconductors has a significantly improved spatial resolution.[1] This has made it possible to

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make the detector smaller and achieve a higher resolution, and has led to the realization of high-precision imaging at low doses. For example, it is effective for evaluating the effectiveness of the impregnation process in aluminum die-cast.(2)

When inspecting aluminum die-cast parts by industrial 3D X-ray CT, it is essential to detect cavities that form inside the aluminum when it solidifies rapidly during casting. To detect cavities, it is necessary not only to check for their presence but also to understand their 3D shape. Cavities with a continuous 3D structure increase the gas flow rate; thus, detecting and dealing with cavities during inspection are necessary.(3) When checking the images imaged by conventional 3D X-ray CT from the sagittal, axial, and coronal directions, it is possible to determine whether there are any cavities and understand their shape in 2D directions. Still, it is difficult to understand the shape of the cavities in 3D directions. Figure 1 shows the visible light image and the images checked from three directions (sagittal, axial, and coronal) of an aluminum die-cast. The sample used in this study has a complex cavity. It is possible to grasp the location and size of the cavities from the cross-sectional images in each direction, but it is difficult to grasp the overall image. In addition, the 3D rendering method is effective for understanding the 3D structure. The main methods are surface rendering, which selects specific results of iso values in the continuous value of voxel values and defines them using a resampling function (iso surface method(4)), and volume rendering, which projects rays from a specific viewpoint direction, calculates the position of the intersection where the rays collide with the object, and adds them together (ray casting method(5)). Figure 2 shows images of the same aluminum die-cast object rendered using surface and volume rendering, and an image from 3D Slicer,(6) a software application for visualizing and analyzing medical image computing datasets. In the case of surface rendering, only the surface of the aluminum die-cast is displayed, and the internal structure of the aluminum die-cast is not shown. In the case of volume rendering, the internal structure of the aluminum die-cast can be seen. Still, the 3D depth relationships are unclear, and it is difficult to grasp the shape and position of the cavities. In addition, although

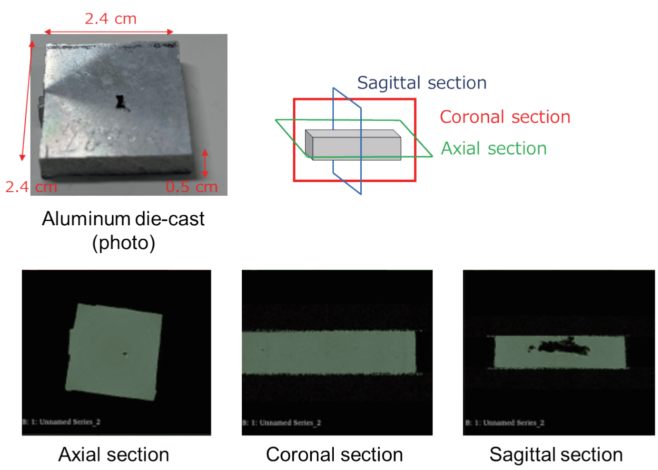


Fig. 1. (Color online) Aluminum die-cast (photo) and reconstructed image obtained by X-ray CT.

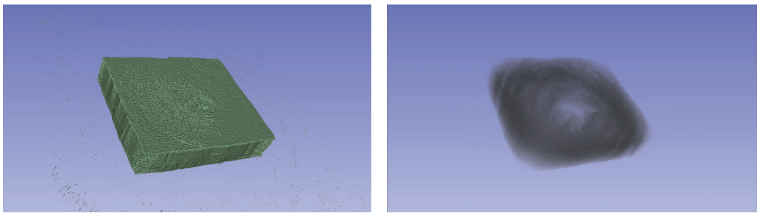


Fig. 2. (Color online) Surface rendering and volume rendering.

both methods can express the 3D structure of simple cavities, it is difficult to express the position and shape of cavities when their shape becomes complex.

## 2. Purpose

In this research, we aim to use mixed reality (MR) technology to intuitively and spatially represent the internal cast cavities' structure of parts that have been imaged by industrial 3D X-ray CT. This will clarify a method of representing the internal structure of objects with complex defect shapes, which was difficult to observe with conventional 2D images and surface rendering. We will clarify how to reproduce the 3D structure of continuous cast cavities in a virtual space using MR, which was difficult to express in sagittal, axial, and coronal sections, and the expression of the internal structure in three dimensions. We will also clarify the segmentation method for internal defects and voids, and express their shape and position in three dimensions.

## 3. Proposed System

The proposed system uses the spatial reality display ELF-SR2(7) from Sony and the Leap Motion Controller 2(8) motion capture device from Ultraleap. Figure 3 shows the proposed system. The data captured by X-ray CT is transferred to a high-performance PC (Windows 11, CPU: 13th Gen Intel® Core™ i9-13900K 3.00 GHz, RAM: 128 GB, Graphics (card): NVIDIA GeForce RTX4090 24GB). On the PC, surface rendering was performed using ZVoxer 5.2.0.0,(9) a 3D image processing platform from Zodiac. We used the gaming engine Unity 2022.3.5f1 to unify the world coordinates in the virtual space. A spatial reality display is connected to the PC, and after detecting the positions of the observer's left and right eyes, the coordinates of the left and right eyes are sent to the PC. Then, by outputting different images on the spatial reality display according to the positions of the left and right eyes via Unity, the observer can check the stereoscopic images according to the viewpoint position. In addition, motion capture is connected to the PC. The system sends the hand's coordinate position to the motion capture driver by capturing the observer's hand movements. Through this system, the observer can understand the internal structure of an object through MR.

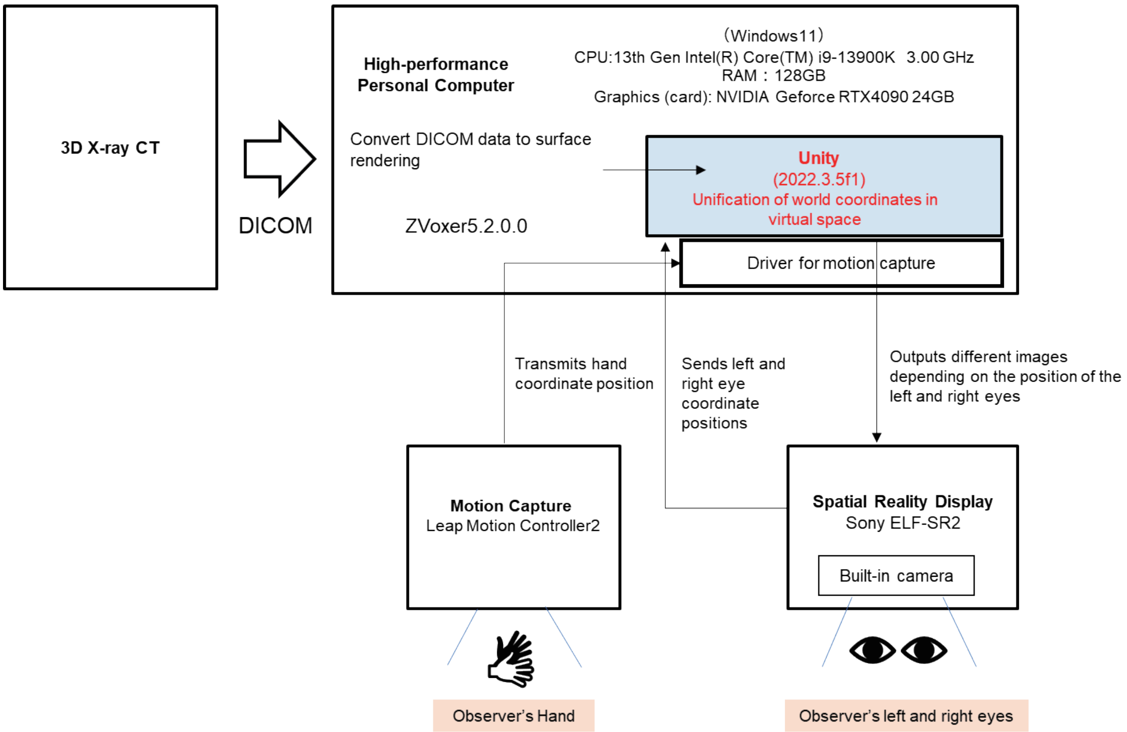


Fig. 3. (Color online) Proposed system diagram.

### 3.1 Device for examination

Figure 4(a) shows a photograph of the spatial reality display ELF-SR2. This display has a built-in eye-tracking sensor that can detect the horizontal, vertical, and depth positions of the user's left and right eyes in real time. This function enables the display to output different images based on the positions and directions of the left and right eyes, thereby achieving 3D image representation. This allows the user to grasp 3D data more intuitively.[10] This display has a limited viewing angle; thus, the 3D images can only be seen within a specific range. For this reason, it is necessary to rotate or move the 3D object to observe it from various directions.

Compared with the commonly used head-mounted displays (HMDs) as MR, spatial reality displays allow users to view images at a closer distance. This allows users to observe the 3D structure within the virtual space in a natural visual environment. As an example of an HMD, HoloLens recommends a hologram installation distance of 1.25 to 5 m.[11] In contrast, spatial reality displays can be used at a closer distance of 0.3 to 0.75 m;[8] thus, a spatial reality display is suitable for this study that requires a detailed observation of the object. Displaying at close range is essential for accurately grasping the shape and position of the defective structure.

To achieve interaction within the virtual space and adjust the display position by moving the subject, Leap Motion Controller 2, a motion capture device, was used. Figure 4(b) shows a photo of this device, which enables users to operate it without using a mouse or touching the screen

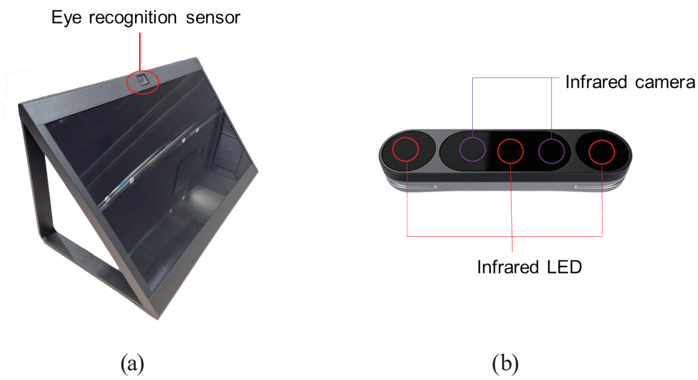


Fig. 4. (Color online) (a) Spatial reality display SONY ELF-SR2 and (b) leap motion conroller 2.

and to do so in a noncontact manner through gestures. It is also composed of two infrared cameras and three infrared LEDs, and it is possible to capture the user's hands and fingers and determine their position in 3D space through image analysis.(12)

With these devices, the observer feels as if the 3D objects pop out at them on the display. The viewpoint position can be changed freely by moving and rotating the object as if grabbing it in real space and changing the viewing direction.

### 3.2 Cross-sectional display method

In surface rendering, the setting at the CT threshold of the model to be displayed significantly impacts the visualization of the internal structure. When the CT threshold is set so that the surface area of the die-cast can be seen, a problem arises in which the cast cavities are displayed as smaller than they are. On the other hand, when the CT threshold was set so that the cast cavities inside the die-cast were visible, missing holes were confirmed to be formed in the surface layer, resulting in the display of a shape different from that of the original model. To solve these problems, we adopted a method in which the transmittance is set to 50% for both the surface layer and the cast cavities and superimposed them, as shown in Fig. 5, so that both the surface layer and the cast cavities can be confirmed.

In setting up the cross-sectional display, we applied a method that our laboratory previously developed for medical applications: superimposing a DICOM image on a surface-rendered cross section.(13) In this study, we extended and adopted this method to visualize complex internal cavity structures in aluminum die-cast samples. In conventional medical CT applications, the target object is typically the human body, where internal density differences between tissues are relatively small, resulting in a lower image contrast. However, owing to the large size of the body, a high spatial resolution is not always required. In contrast, aluminum die-cast components consist of regions with high-density material (aluminum) and low-density voids (air), leading to high-contrast imaging. Nevertheless, the small physical size of these industrial objects requires high-resolution scanning and detailed visualization to capture fine internal defect structures such as porosities (casting voids).

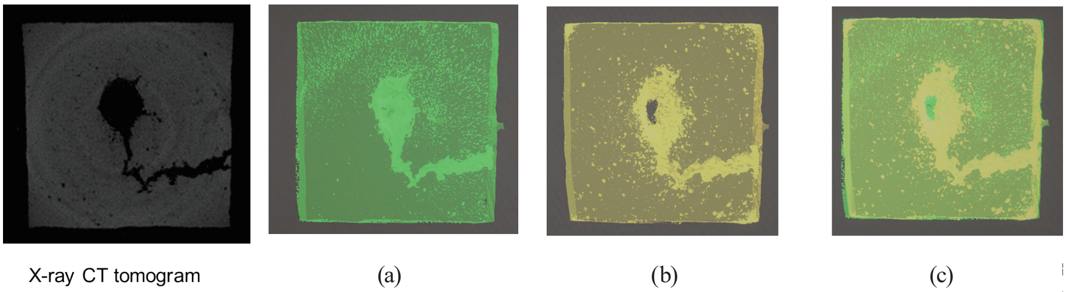


Fig. 5. (Color online) CT threshold value setting for models to be displayed. Threshold values obtained (a) on the surface and (b) in the casting nest area, and (c) composite of (a) and (b) models with semi-transparency.

Furthermore, unlike in the medical field where the interest lies in identifying anatomical structures or abnormalities, in aluminum die-casting, the focus is on understanding how internal cavities such as blowholes or shrinkage defects are spatially distributed and interconnected in three dimensions. This requires not only an accurate detection of internal voids but also a precise spatial representation to assess defect propagation paths or penetrations. Figure 6 shows the proposed method. To illustrate the comparison with volume rendering, volume rendering renders only from a specific viewpoint, making it difficult to grasp the internal structure fully. On the other hand, in the proposed method, the observer first specifies the position and angle of the cross section they wish to observe. Next, a cross-sectional view in the 2D direction was generated from the DICOM data according to the position and angle of the specified cross section. By superimposing the generated cross section on the surface-rendered model, it is possible to grasp the internal structure while expressing it three-dimensionally. This method enables the representation of complex internal structures, which was difficult with surface rendering, and the representation of 3D front-back relationships, which was difficult with volume rendering. Figure 7(a) illustrates the relationship between boundary surfaces, cross sections, and visible/invisible objects. Figure 7(b) shows a cross section when surface rendering is applied to the object, Fig. 7(c) shows a cross section when volume rendering is applied, Fig. 7(d) shows a 2D cross section based on DICOM, and Fig. 7(e) shows the 2D cross section based on DICOM overlaid on the object cross section rendered by surface rendering. Figure 7(b) shows the surface layer of the target object meshed, enabling the expression of three-dimensionality and shading, making it easier to grasp the spatial structure in the depth direction. However, it is difficult to represent the complex structure of cast cavities by surface, which could hide some of the complex geometry. Figure 7(c) reflects transparency based on CT value density information, displaying the shape of cast cavities as density information. However, when cross sections are displayed, it is difficult to determine the position of the cross section and pression by density has limitations in expressing uneven structures. Figure 7(d) is a 2D image generated from DICOM voxel data, but it cannot represent 3D structures as an image. Therefore, the new representation method [Fig. 7(e)] is a representation combining a 2D cross-sectional image obtained from DICOM with a cross section in the same position as in surface rendering. This method complements the advantages and disadvantages of surface rendering and volume rendering, enabling the understanding of both internal structures and depth.

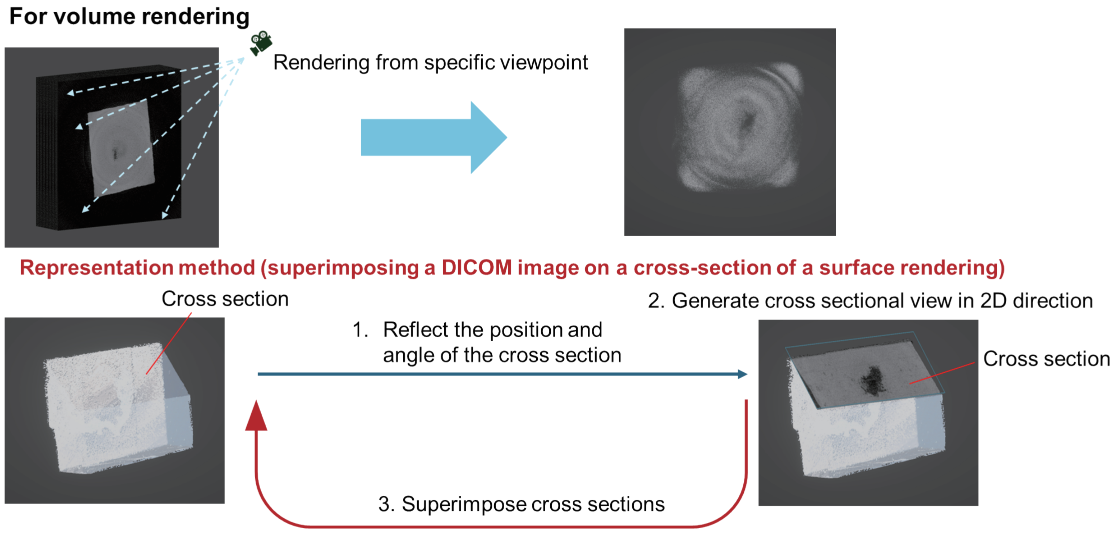


Fig. 6. (Color online) Method of superimposing DICOM images on cross sections rendered by surface rendering. (For visual comparison, surface rendering displays object surfaces in white, while volume rendering uses white tones to represent internal density.)

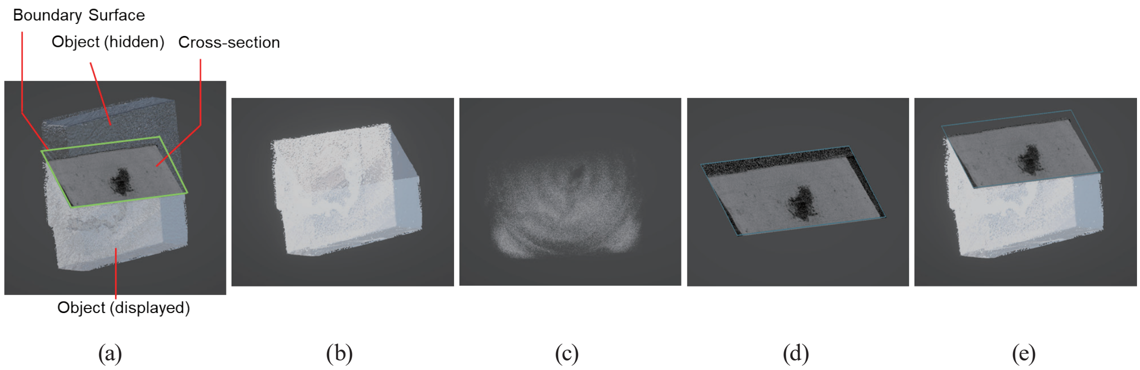


Fig. 7. (Color online) (a) Relationship between boundary surfaces, cross sections, and displayed and hidden objects. (b) Surface rendering, (c) volume rendering, (d) DICOM 2D image, and (e) surface rendering cross section with DICOM 2D image. (For visual comparison, surface rendering displays object surfaces in white, while volume rendering uses white tones to represent internal density.)

### 3.3 Motion capture and cross-sectional display

In this study, in an MR environment, the 3D objects and cross sections can be freely moved and rotated according to the observer's viewpoint direction using motion capture instead of a mouse or keyboard to represent the internal structure more clearly. The 3D object, cross section, and boundary surface are set as shown in Fig. 8. The observer moved the 3D model or the boundary surface, and the cross section was displayed when the boundary surface and the 3D model came into contact. In addition to the 27-inch spatial reality display used in this system, the motion capture detection angle was 160 degrees horizontally and vertically, sufficient to detect

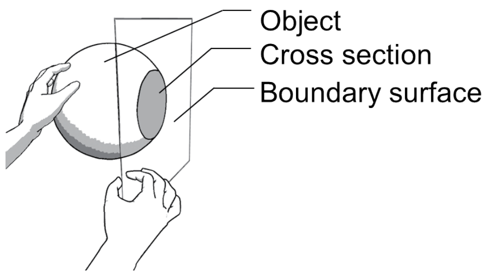


Fig. 8. Object, cross section, and boundary surface.

both hands. By enabling a two-handed operation, it is possible to view the sample as if it were held in one's hand and check inside by moving the cross-sectional object with the right hand until the 3D object remains fixed with the left hand. Compared with touch operation with a mouse or tablet, this method is closer to finding an object's crusts, fatigue, or damage in real space, thus enabling spatial understanding.

## 4. Experiment Overview

The X-ray CT imaging of an aluminum die-cast part was performed to visualize its internal structure in a mixed-reality representation. The sample aluminum die cast has complex internal voids. The imaging environment is shown in Fig. 9. The aluminum die cast was placed on a rotating stage and rotated while being imaged with a photon-counting semiconductor X-ray detector. X-ray tube voltage, current, object, detector, and X-ray source conditions are shown in Table 1.

Subsequent procedures are described below. The imaging data was acquired in DICOM format. The back projection method was used in the reconstruction technique. Surface rendering was performed according to two threshold values, one for the surface layer and the other for the cast area, and a model according to the two threshold values was synthesized translucently in Unity and placed in the virtual space, and cross-sectional images were generated in real time. ELF-SR2 and Leap Motion Controller 2 were used to represent the internal structure of the object in the virtual space and check it in any position and direction.

## 5. Experimental Results

Each device enabled the observer to rotate and move the object using hand gestures and observe the cross section from any direction. An aluminum die cast with complex cavities was imaged by X-ray CT. Figure 10 shows cross sections from the sagittal, axial, and coronal sections. This is the same sample displayed in Fig. 1, but the cross-sectional position was changed to match the center position of the casting nest structure. With this system, the spatial connections between successive casting cavities, which were difficult to grasp with conventional

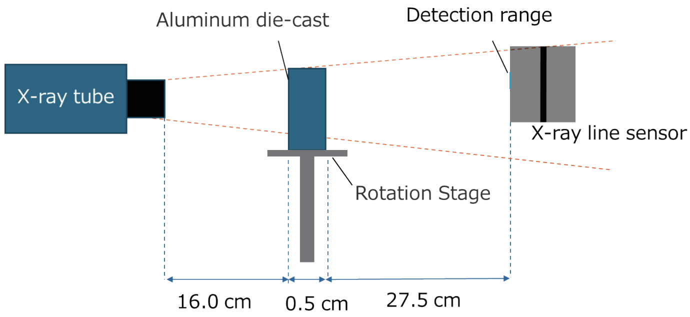


Fig. 9. (Color online) Experimental conditions.

Table 1
Imaging conditions.

| | |
|---|---|
| X-ray tube voltage | 150 (kV) |
| X-ray tube current | 200 (μA) |
| Object | Aluminum die-cast parts |
| Detector | X-counter (Varex Imaging) |
| X-ray source | Microfocus X-ray source L12161-02 (Hamamatsu Photonics) |

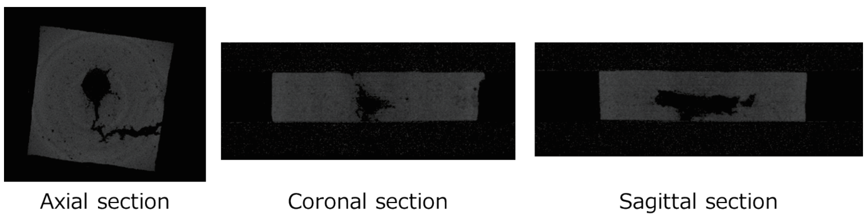


Fig. 10. 2D cross-sectional images.

3D visualization methods, can now be clearly identified. In particular, as shown in Fig. 11, by changing the cross-sectional position while continuously observing the axial and coronal sections, it was possible to visually confirm the spreading of the casting nests and the presence of penetrating structures. This method allows users to adjust the cross-sectional plane freely, making it possible to observe both the penetration path of a porosity and its extent within the same slice, as demonstrated in Fig. 12. This provides a significant advantage in understanding complex internal structures in small-scale, high-precision industrial components.

Also shown in Fig. 13 is a photograph represented by the spatial reality display. In this system, the characteristics of the spatial reality display, SONY's ELF-SR2, enabled real-time parallax adjustment based on line of sight, facilitating 3D object recognition. In addition, the following intuitive operations were confirmed to be possible by using motion capture:

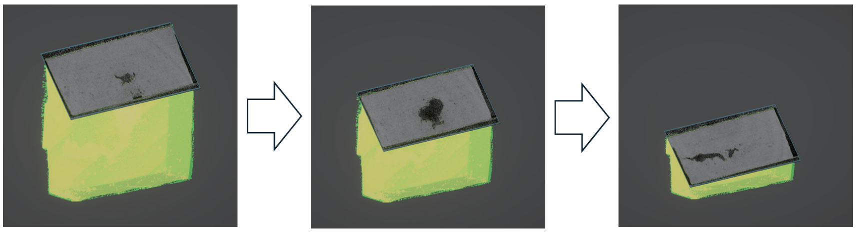

Fig. 11. (Color online) The cross section changes with the position of the boundary surface.

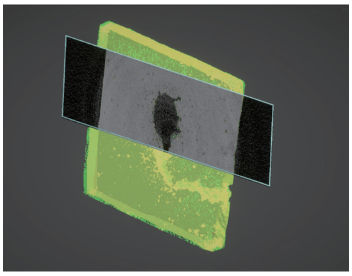

Fig. 12. (Color online) Appearance of a through hole in the casting and appearance of defects in terms of shape and size in cross section.

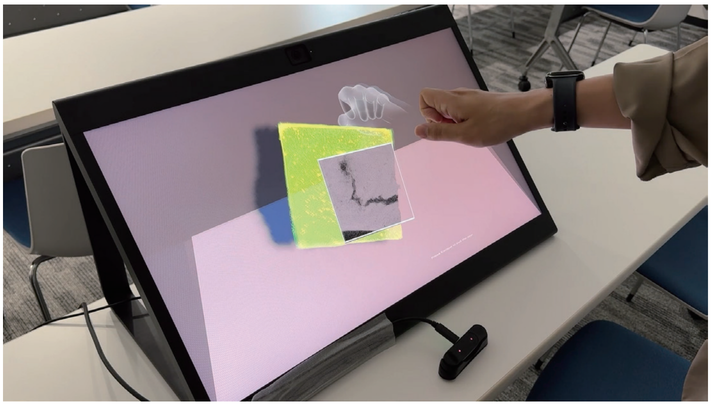

Fig. 13. (Color online) Experimental conditions: the observer moves and rotates 3D objects and boundaries with hand movements. By changing the position of the observed cross section, the complex structure of the casting cavity can be understood spatially.

- An object can be observed from different viewpoints while rotating and moving it with one hand.
- The object can be manipulated using both hands (holding the object with one hand while shifting the cross section with the other).
- Users can understand the shape of internal defect structures (e.g., cast cavities) three-dimensionally by freely changing the orientation and position of the cross section.

These methods are superior to mouse and keyboard operations in that they allow users to freely manipulate objects in 3D space through intuitive and natural movements, providing a sense of actually handling the target object and enabling the confirmation of its internal structure. However, the following challenges have been identified with this approach. The limited field of view of the spatial reality display makes it difficult for two or more people to observe simultaneously, necessitating improvements for future multi-user support. Additionally, motion capture-based operations require learning, and users unfamiliar with the system tend to experience a reduced operational accuracy. To address these challenges, we are exploring the development of a light field display version for shared experiences among multiple users and the introduction of machine-learning-based gesture correction functionality.

## 6. Conclusion

In this study, we proposed a method of easily spatially representing the defect structure of parts imaged by industrial 3D X-ray CT using MR technology by imaging an aluminum die-cast by X-ray CT and representing it by ELF-SR2 and Leap Motion Controller 2.

The surface-rendered model is superimposed on a DICOM-generated cross-sectional image, enabling an intuitive understanding of the internal structure, which has been difficult with conventional 2D cross-sectional images or 3D visualization from a fixed viewpoint. The superimposition of multiple surface-rendered models with different threshold values in semitransparency enables the segmentation of internal defects and voids without missing any defects and a 3D representation of the shape and position of defects.

The MR environment proposed in this study was effective as an intuitive visualization method for X-ray CT data. In the future, it is expected to facilitate the spatial understanding of internal structures in the nondestructive inspection of objects with complex shapes, such as automobile parts and precision components. Further development of MR technology visualization methods is required in manufacturing processes' quality control and design optimization.

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