Neutron/X-ray Dual-Modality Imaging at ERNI: A Case Study on Cultured Pearls

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Abstract

X-ray and neutron computed tomography (CT) are widely used for non-destructive characterization of internal structures. Their distinct contrast mechanisms, arised from different interactions with matter, can enhance structural analysis when combined. Dual-modality imaging integrating both techniques can overcome the limitations of single-modality approaches. In this study, we performed X-ray and neutron CT experiments on cultured pearl samples using the Energy-Resolved Neutron Imaging (ERNI) instrument at the China Spallation Neutron Source (CSNS). A multi-step registration pipeline based on edge extraction and rigid 3D transformation was developed to align and fuse the datasets. The results demonstrate the potential of dual-modality imaging for enhanced structural visualization of materials with complex internal structures

Full Text

Preamble

Neutron/X-ray Dual-Modality Imaging at ERNI: A Case Study on Cultured Pearls∗

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mechanisms, arising from different interactions with matter, can enhance structural analysis when combined. Dual-modality imaging integrating both techniques can overcome the limitations of single-modality approaches.

In this study, we performed X-ray and neutron CT experiments on cultured pearl samples using the Energy-Resolved Neutron Imaging (ERNI) instrument at the China Spallation Neutron Source (CSNS). A multi-step registration pipeline based on edge extraction and rigid 3D transformation was developed to align and fuse the datasets. The results demonstrate the potential of dual-modality imaging for enhanced structural visualization of materials with complex internal structures.

Keywords: Dual-modality imaging; X-ray computed tomography; Neutron computed tomography; Image registration; Pearls

Introduction

Dual-modality imaging, combining X-ray and neutron computed tomography (CT), has emerged as a powerful non-destructive technique for comprehensive characterization of complex materials. X-ray CT relies on interactions with electrons and is highly sensitive to variations in electron density and atomic number, thereby providing high-resolution visualization of structural features in high-Z or dense materials. In contrast, neutron CT relies on nuclear interactions and is particularly sensitive to low-Z elements such as hydrogen, enabling the detection of organic matter and internal features that are often invisible in X-ray imaging [2]. The complementary contrast mechanisms of these two modalities enable dual-modality imaging to deliver more complete information regarding the internal structure and composition of heterogeneous and composite systems. This imaging approach has found widespread applications in diverse fields, including materials characterization, geosciences, battery diagnostics, and cultural heritage analysis [3–6].

A fundamental challenge in dual-modality imaging lies in the accurate registration of datasets acquired from modalities with inherently different physical contrast mechanisms, spatial resolutions, and noise characteristics. Image registration aligns images of the same object acquired at different times or using different modalities, enabling joint analysis and comparison.

In the broader field of multimodal image registration, numerous handcrafted feature descriptors have been developed over the past decades to address modality differences—such as Edge Orientation Histograms (EOH), Scale-Invariant Feature Transform (SIFT), and Speeded-Up Robust Features (SURF)—which are often adapted to suit cross-modality conditions [7–9]. These methods, while effective in certain scenarios, typically exhibit limited robustness when facing large inter-modality disparities in contrast and appearance. In recent years, artificial intelligence (AI) techniques, particularly those employing convolutional neural networks (CNNs), have been increasingly adopted to improve registration accuracy and robustness [10]. Deep learning-based image-to-image translation approaches, such as those based on Generative Adversarial Networks (GANs), have also been explored to convert the multimodal registration problem into a monomodal one, which is often easier to solve [11]. Nevertheless, the significant heterogeneity between neutron and X-ray CT datasets—especially when imaging complex composite materials—presents unique challenges. This highlights the need for continued development and optimization of registration algorithms specifically tailored to this dual-modality imaging context.

Pearls, as biomineral composites consisting of mineralized aragonite layers and organic matrix, represent a paradigmatic example of structurally intricate natural materials whose internal features are critical to their quality and formation processes [12]. While conventional single-modality imaging techniques have provided valuable insights into pearl microstructure, the integration of neutron and X-ray CT offers complementary contrast enabling enhanced visualization of both mineral and organic constituents [13-15]. This makes pearls an ideal model for validating the potential of dual-modality CT in biomineralized materials research. However, translating such imaging potential into practical applications remains challenging, particularly within the domestic research context.

Although dual-modality imaging systems have been extensively explored in international research, practical applications within China remain relatively scarce. Most domestic efforts have focused on conceptual system designs or algorithm development, with few experimental implementations based on real imaging data [16-19]. For example, Yang' s team at Tsinghua University developed a hybrid imaging system that simultaneously generates X-rays and photoneutrons using a high-energy electron linac [20]. This co-linear design, based on bremsstrahlung and moderated photoneutrons from a tungsten target, enables synchronized acquisition of neutron and X-ray images with minimal geometric offset, facilitating fusion. However, this system faces challenges such as a large flux discrepancy and strong radiation coupling, which complicates the independent tuning of each modality and the stability of neutron detection under high X-ray background. Moreover, existing studies have primarily focused on 2D radiography or fusion algorithms, with limited emphasis on 3D tomographic registration or material-specific structural analysis.

In this context, our study presents one of the first reported experimental demonstrations of volumetric dual-modality imaging conducted on a large-scale neutron imaging beamline in China. Conducted on the Energy-Resolved Neutron Imaging (ERNI) instrument at the China Spallation Neutron Source (CSNS), our work shows a feasible joint CT acquisition strategy combined with a customized cross-modality registration pipeline, specifically tailored to the structural imaging challenges presented by pearl samples. By leveraging the complementary contrast mechanisms of neutrons and X-rays, this approach enables detailed structural characterization beyond the capacity of single-modality imaging. More importantly, it establishes a practical foundation for future dual-modality research on multimaterial systems using high-intensity, independently tunable neutron and X-ray sources, offering a scalable framework for applications in materials science and beyond.

II. Materials and Methods

A. Sample

The specimens used in this study were two Baroque pearls, measuring 1.82×1.90×2.24 cm and 1.85×1.93×2.51 cm, respectively, as illustrated in Figure 1 [Figure 1: see original paper]. These samples are beaded cultured pearls, formed by inserting a spherical bead nucleus into the gonad of the oyster, around which nacre is secreted by the surrounding mantle tissue [21]. Due to the non-uniform deposition of nacre layers during the biomineralization process, the resulting shapes of Baroque pearls are highly irregular and asymmetric. Structurally, each pearl consists of a dense core primarily composed of calcium carbonate in the form of aragonite, originating from the implanted bead. This core is surrounded by multiple layers of nacre, which also contain aragonite platelets interspersed with organic biopolymers such as conchiolin. The heterogeneous composition, combined with the complex growth morphology, makes Baroque pearls a representative model for evaluating the capabilities of dual-modality imaging.

B. Experimental Setup

1. Overview of the ERNI Instrument at CSNS The CT experiments were conducted at the Energy-Resolved Neutron Imaging (ERNI) instrument, located on beamline 13 at the China Spallation Neutron Source (CSNS) [22, 23]. ERNI is the first facility in China specifically dedicated to pulsed neutron imaging and is designed as a versatile platform for multi-scale, multi-dimensional, and multi-modality material characterization. It supports a wide range of analytical techniques, including conventional neutron radiography and tomography, Bragg-edge neutron imaging, neutron grating interferometry, neutron resonance imaging, neutron diffraction, as well as complementary X-ray tomography. The total instrument length is 43.1 meters, with the scattering room beginning at 25 meters. A pinhole selector positioned at 24.78 meters provides interchangeable apertures with diameters of 5, 10, 20, 40, and 80 mm to tailor the neutron beam size for different imaging requirements. ERNI features two dedicated sample positions—Position 1 at 30 meters and Position 2 at 35 meters—accommodating diverse imaging modalities and scientific applications.

2. Neutron and X-ray Tomography X-ray and neutron radiography are widely used non-destructive imaging techniques that produce two-dimensional projection images based on the differential attenuation of radiation as it passes through an object. These two modalities rely on different physical interaction mechanisms and provide complementary contrast. Building upon these two-dimensional approaches, computed tomography (CT) extends radiography into three dimensions by acquiring a series of projection images as the sample is rotated incrementally, typically over a 360° range. These projections, which record the spatially varying attenuation of incident X-rays or neutrons, are then processed using mathematical reconstruction algorithms–such as filtered back projection (FBP) or iterative reconstruction methods–to generate a volumetric map of internal attenuation coefficients. This enables detailed 3D visualization of internal structures without physically altering or sectioning the object. X-ray and neutron CT are complementary techniques in multimodal imaging, and the integration of both modalities offers a more comprehensive understanding of complex, heterogeneous materials.

In this study, neutron tomography was conducted at Position 2 of ERNI. The pinhole was moved to 20 mm and the neutron wavelength range was set between 0.5 and 4.6 Å, selected by choppers. For neutron tomography, all projections were recorded using a neutron detector comprising a 50 µm thick ZnS/6LiF scintillator screen, a CCD camera (Andor, Oxford Instruments), and optics equipped with a Nikon photo lens (Nikon, Japan). The camera array has a size of 2048×2048 pixels with a pixel size of 13.5 µm. The magnification of the optical lens was adjusted to approximately 2×, resulting in a field of view (FOV) of 5.5×5.5 cm^2. A scan of 641 projections from 0 to 320 degrees with an angular step of 0.5° was performed, with an exposure time of 100 seconds for each projection.

X-ray tomography was performed at sample Position 1 of ERNI using a microfocus X-ray source (X-ray WorX GmbH, Germany), operated at 80 kV and 125 µA. The sample was mounted on a high-precision rotational stage and scanned over 360° with a step size of 0.25° per projection. For each projection, the exposure time was 1 second. A flat-panel detector (Shad-o-Box, Teledyne DALSA) was used to record the transmitted X-rays. The detector consists of 2940×2304 pixels with a pixel size of 49.5 µm. The cone-beam geometry yields a geometric magnification factor of approximately 1.2×.

Image Processing and Registration Method

1. Reconstruction and Preprocessing For the X-ray CT data, the Feldkamp-Davis-Kress (FDK) algorithm was employed to reconstruct volumetric images from cone-beam projections acquired over a full 360° rotation [24]. Prior to reconstruction, each projection was normalized using the corresponding flat-field and dark-field images to compensate for inhomogeneous detector response and beam fluctuations. In addition, a projection-domain ring artifact correction algorithm was applied to suppress ring-shaped artifacts commonly arising from defective detector elements or non-uniform gain [25].

For neutron CT, image reconstruction was carried out using a standard filtered back-projection (FBP) algorithm [26]. The same flat-field and dark-field normalization was applied to the raw neutron projections. Due to the inherently low neutron flux and the resulting low signal-to-noise ratio (SNR), median filtering was applied to the raw projections prior to reconstruction in order to suppress random noise. The same ring artifact correction algorithm was also applied to reconstructed slices. However, during neutron data acquisition, a temporary beam instability led to the loss of projection data over an angular range of approximately 10°, resulting in angular undersampling artifacts. These artifacts manifested as localized streaks and elevated noise levels in the reconstructed slices (Figure 4 Figure 4: see original paper), introducing non-negligible distortions that complicate image registration.

Following reconstruction, both volumetric datasets were resampled to isotropic voxel spacing using linear interpolation. All datasets were exported in 8-bit format and processed by custom MATLAB scripts [27].

2. 3D Registration Framework To accurately align the reconstructed X-ray and neutron volumes, a multi-step registration pipeline was implemented. Due to significant differences in resolution, contrast, and noise levels between the two modalities, direct intensity-based registration approaches (e.g., mutual information) were found to be insufficiently robust, particularly for the neutron CT data affected by undersampling artifacts.

To overcome this limitation, an edge-based registration strategy was adopted. The key idea is to extract structural contours from both imaging modalities, as edges tend to be more invariant to noise, intensity non-uniformity, and modality-specific artifacts. To achieve this, the Canny edge detection algorithm was applied to both X-ray and neutron CT volumes [28]. The Canny operator was selected for its strong robustness in preserving geometric boundaries while suppressing background noise—making it particularly suitable for multimodal registration under different imaging conditions. The Canny edge detection process consists of the following main steps: (1) Gaussian filtering to smooth the image and suppress noise; (2) Gradient calculation to identify regions of rapid intensity change; (3) Non-maximum suppression to thin out edges and localize them precisely; (4) Double-threshold detection followed by edge tracking to distinguish true edges from noise. Another key advantage of the Canny method lies in its tunability through dual thresholds, which allows flexible control over edge continuity and the ability to isolate well-defined external contours.

The extracted edge volumes were first binarized, and a coarse alignment was performed by matching the centroids of the two volumes to approximately align their spatial positions. For fine registration, the MATLAB built-in function `imregister` was employed to estimate a rigid transformation between the edge images [29]. This function performs intensity-based image registration using an affine transform model, and in this case, it was constrained to rigid transformations (translation and rotation only). The registration algorithm relies on a multiresolution pyramid scheme, optimizing a similarity metric—in this case, Mattes mutual information—via a gradient descent optimizer to iteratively refine the alignment between the moving (X-ray) and fixed (neutron) images. The resulting transformation matrix was finally applied to resample the neutron volume into the coordinate space of the X-ray reference for subsequent fusion and analysis.

As shown in Figure 3 [Figure 3: see original paper], this edge-driven registration framework effectively mitigated the influence of undersampling artifacts in the neutron data and enabled accurate structural alignment despite the heterogeneity of the input volumes. The registered datasets were evaluated for spatial consistency, as discussed in Section 3. All image processing procedures were conducted using MATLAB and Avizo [28, 30].

III. Results and Discussion

In this section, we present and describe the structural features revealed by each imaging modality for both pearl samples. Each neutron CT slice provides a two-dimensional distribution of attenuation coefficients, where brighter pixels indicate regions of higher neutron attenuation. Similarly, the X-ray CT images reflect the X-ray attenuation, which is generally proportional to the atomic number. As a result, brighter areas in the X-ray images correspond to regions with higher atomic number and stronger X-ray absorption.

A. Imaging of X-ray and Neutron CT

Figure 4 presents representative reconstructed slices of pearl sample 2 obtained from X-ray and neutron computed tomography (CT). Owing to the high photon flux and superior spatial resolution of the X-ray system, the X-ray CT slice clearly delineates the boundary between the pearl nucleus and the surrounding nacre. These regions are primarily composed of calcium carbonate, which exhibits strong X-ray attenuation and thus appears as bright white areas in the image. Additionally, the high resolution of X-ray CT allows for the visualization of micro-scale growth lines within the nacre, as well as internal defects within the nucleus—highlighted by the yellow box in Figure 4(b). In contrast, the neutron CT slice reveals features rich in hydrogen, such as internal organic matrices or water-containing regions, which are either poorly visible or invisible in the X-ray image. These regions are marked by the red box in Figure 4(a). Although the spatial resolution of neutron CT is lower due to limitations imposed by the scintillator thickness and beam flux, it provides unique sensitivity to light elements, particularly hydrogen.

The observed contrast differences between X-ray and neutron CT images originate from the fundamentally distinct physical interaction mechanisms involved in each modality. X-ray attenuation is primarily governed by photoelectric absorption and Compton scattering, both of which scale strongly with the atomic number (Z) of the material. As a result, high-Z elements such as calcium exhibit significant attenuation, making X-ray CT highly effective in visualizing dense, mineralized structures like the calcium carbonate found in pearl nuclei and nacre layers. However, X-rays are relatively insensitive to low-Z elements, particularly hydrogen, due to their low electron density, rendering organic materials largely transparent in X-ray images. In contrast, neutron attenuation arises from nuclear interactions, which are highly dependent on the specific isotopic composition of the material rather than its atomic number. Notably, hydrogen—despite its low atomic number—possesses a high neutron scattering cross-section, and even small amounts can produce strong contrast in neutron images. This makes neutron CT particularly well suited for detecting hydrogen-rich components such as organic matrices and water that are otherwise difficult to detect using X-ray imaging.

Taken together, the two imaging modalities provide mutually complementary structural information. While X-ray CT excels in resolving dense, mineralized structures, neutron CT provides unique access to the organic phases. This duality underscores the necessity for data integration and motivates the image registration and fusion framework described in subsequent sections.

B. Registration Accuracy and Validation

To ensure meaningful fusion of the dual-modality datasets, a rigid 3D registration framework based on edge extraction was applied. External boundaries were extracted from both the neutron and X-ray CT volumes using the Canny edge detector, enabling robust alignment under conditions of contrast disparity and noise. This approach significantly enhanced the structural consistency between modalities and minimized the influence of modality-specific artifacts. An initial spatial alignment was achieved by matching the centroids of the two volumes, followed by fine registration using the MATLAB function `imregister`, which optimizes rigid transformations via mutual information. The final transformation matrix was applied to resample the neutron volume into the coordinate system of the X-ray dataset.

To intuitively assess the accuracy of the image registration, a checkerboard composite image was generated using representative slices from the registered neutron and X-ray datasets (Figure 5 [Figure 5: see original paper]). In this 2×2 grid arrangement, the top-left and bottom-right quadrants correspond to patches from the neutron CT image, while the top-right and bottom-left quadrants display the corresponding regions from the X-ray CT image. As evident from the well-aligned structures at the quadrant interfaces, the registration achieves high spatial consistency across the two datasets, with no noticeable discontinuities or mismatches observed at the transitions between modalities. In particular, the color-fused image in Figure 6 Figure 6: see original paper clearly highlights the precise correspondence of structural features between modalities, serving as a compelling visual confirmation of registration accuracy.

These results demonstrate that the proposed multi-step registration method is robust and accurate for rigidly aligning dual-modality CT data, even in the absence of clearly corresponding gray-level intensities. The use of structural edges as alignment cues effectively bridges the contrast gap between the two modalities and avoids convergence to local minima.

C. Structural Interpretation from Fused Images

After successful registration, corresponding X-ray and neutron slices were compared to illustrate their complementary characteristics, as shown in Figure 6(a) and Figure 6(b). Slices from Pearl 1 are presented in the first row, and those from Pearl 2 are in the second row. As previously discussed, X-rays and neutrons exhibit sensitivity to different components within the pearls. The high spatial resolution and signal-to-noise ratio of X-ray CT allow for clear visualization of growth patterns during pearl formation, as indicated by the red dashed boxes. These structures are barely distinguishable in the neutron images. Additionally, since the pearl core is primarily composed of calcium carbonate, which strongly attenuates X-rays but only weakly attenuates neutrons, the core structure is clearly delineated in the X-ray images (white dashed boxes), including internal microstructures such as pores marked by white arrows.

In contrast, neutron imaging provides unique sensitivity to hydrogen-rich substances such as water or organic matter. Structures enclosed by yellow dashed boxes exhibit strong neutron attenuation but low X-ray attenuation, which likely indicates the presence of organic residues involved in pearl formation. Meanwhile, the regions outlined in blue dashed boxes display significant attenuation in neutron images but little to no attenuation in X-rays, suggesting the presence of retained moisture. Such detailed compositional information cannot be fully captured by either modality alone, demonstrating the powerful synergy of dual-modality imaging.

A comparative analysis of the two pearls reveals further insights. In Pearl 1, internal voids appear as low-attenuation regions (dark areas) in both X-ray and neutron images, as marked by white arrows, suggesting the presence of air or low-density inclusions. In contrast, the core of Pearl 2 exhibits low attenuation in X-rays but high attenuation in neutrons (blue arrows), indicating possible residual organic channels or water content. This observation suggests that Pearl 2 may contain more moisture or retain a more intact organic matrix than Pearl 1.

Following this analysis, a fused volume was generated using pseudo-color channel mapping, as shown in Figure 6(c). X-ray data were assigned to the green channel and neutron data to the red channel, with overlapping features rendered in yellow. Modality-specific features appear in their respective colors, providing an intuitive and effective visualization of the structural correspondence and complementary contrast. The fused volume encapsulates comprehensive information from both modalities, enabling simultaneous identification of features such as organic matter, moisture, cracks, and pores—a capability that cannot be achieved with a single modality alone.

This complementary imaging strategy significantly enhances the interpretability of complex composite materials like pearls, where understanding the internal organic–inorganic interface is essential for evaluating mechanical integrity and formation history. The fused volume not only provides a more holistic structural depiction but also lays the foundation for downstream applications such as automated segmentation and quantitative analysis of heterogeneous components.

D. Applicability and Limitations of the Method

The presented dual-modality imaging and registration framework demonstrates strong potential for application in a broad range of scientific fields. Besides biomineralized samples such as pearls, the method could be extended to materials characterization, geosciences, battery diagnostics, and cultural heritage analysis.

However, both CT modalities have inherent limitations. CT imaging requires the acquisition of a large number of projections followed by computationally intensive reconstruction. This is particularly challenging for neutron CT due to its inherently low flux, resulting in long acquisition times—often several hours for a complete dataset. In addition, ring artifacts caused by detector inhomogeneities are commonly observed in both neutron and X-ray reconstructions. Although ring artifact correction was applied during preprocessing, residual artifacts remained and could not be entirely eliminated. During dual-modality analysis, care must be taken to avoid misinterpreting these artifacts as structural features. The proposed registration method, while effective, is currently limited to rigid transformations and relies on reliable edge extraction. This makes it well suited for rigid, non-deformable samples such as pearls, yet its direct application to soft or deformable samples may be limited without further adaptation.

Future improvements could incorporate deep learning-based segmentation and feature extraction to improve robustness and reduce user intervention. Non-rigid registration frameworks could also be explored to handle complex deformation scenarios. Nevertheless, the method presented here provides a practical, accurate, and interpretable solution for dual-modality CT data fusion, with significant utility in multimodal imaging studies.

IV. Conclusion

In this study, dual-modality imaging combining X-ray and neutron computed tomography (CT) was successfully applied for the non-destructive structural characterization of cultured pearls. Leveraging the complementary contrast mechanisms of the two modalities, the internal features of both mineralized and organic components were visualized with improved clarity and completeness.

To address the challenge of dual-modality registration, a robust multi-step registration framework based on edge extraction and rigid 3D transformation was developed. This method enabled accurate spatial alignment and effective data fusion, facilitating integrated analysis of complex composite microstructures.

The results highlight the potential of dual-modality imaging for comprehensive structural assessment of complex materials. Despite its advantages in contrast complementarity and spatial correlation, challenges remain in data processing complexity and registration accuracy—particularly for non-rigid conditions.

Future efforts will focus on incorporating artificial intelligence-based approaches to enhance registration automation and robustness. In addition, the co-located neutron and X-ray facilities provide a unique platform for in situ dual-modality imaging, enabling future studies on dynamic processes and functional materials.

The proposed methodology holds promise for broader application in biomineralized systems, cultural heritage preservation, and multi-phase materials requiring non-destructive, multi-contrast imaging. As the first publicly documented volumetric dual-modality CT experiment conducted on a large-scale neutron imaging facility in China, this work establishes a valuable technical foundation for future developments in multimodal imaging at national research platforms.

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Note: Figure translations are in progress. See original paper for figures.