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Sub-Micron Resolution Optical-Lens Coupled with X-ray Image System via Deep Learning

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1. Introduction

Micro-X-ray imaging systems have found extensive application across various scientific domains, including biology, non-destructive testing (NDT) of electronics, and material science. These areas exemplify the versatility of micro-X-ray imaging techniques. The predominant approach of Micro-X-ray is the geometric magnification method. This method operates under the premise that an X-ray tube's focal spot is treated as a point rather than an area. This consideration allows micro-focus X-ray imaging systems to derive their geometric magnification parameters from the distances between the X-ray tube's focal spot and both the object and the detector.

Notably, the geometric magnification method permits achieving sub-micron resolution utilizing a 2μm focal spot X-ray tube. However, the high cost and large volume of such X-ray tubes pose limitations. [1] To address these concerns, our study introduces an innovative approach involving an optical-lens coupled X-ray imaging system. Within this configuration, X-rays emitted by the X-ray tube traverse the object and interact with a scintillator screen. Positioned behind the scintillator screen is an optical microscope, which captures micro-resolution images by enlarging the visible light image projected onto the scintillator screen. Importantly, this system dispenses with the geometric magnification method in favor of optical lens-based magnification, significantly mitigating blurring attributed to the X-ray tube's focal spot.

The adoption of an optical-lens coupled X-ray imaging system brings notable advantages. By embracing larger focal spot X-ray tubes, the system becomes both cost-effective and compact. It is important to acknowledge, however, that this system has inherent limitations; the minimum achievable resolution is constrained to the range of 1-2 μm due to blurring caused by the numerical aperture of the objective lens and the scintillator's thickness. [2]

To surmount these limitations, our study endeavors to transcend the sub-micron resolution barrier through the application of a super-resolution deep learning algorithm. This innovation holds the promise of unlocking unprecedented imaging precision within the optical-lens coupled X-ray imaging system.

2. Methods and Results

2.1 Designed System

The optical-lens coupled X-ray imaging system comprises a micro-focus X-ray tube (P030-24-12F100W, Petrick GmbH, Bad Blankenburg, Germany), an optical lens, and a scientific complementary metal-oxide-semiconductors (sCMOS) detector (pico.edge 4.2, PCO, Kelheim, Germany). The micro-focus X-ray tube operates at an operating voltage and current of 50 kVp and 1 mA, respectively. The focal spot size is within the range of 30–55 μm. To achieve magnification of the X-ray image on the scintillator film, a 20x infinity corrected objective lens (f = 200 mm) and a tube lens (f = 160 mm) are employed. Subsequently, the developed image is captured using the sCMOS detector, which features a 6.5 μm square pixel size.

In the context of this study, the tomosynthesis reconstruction method was applied. Tomosynthesis is adept at reconstructing both sliced and three-dimensional (3D) images of objects by integrating multiple two-dimensional (2D) projected images from various angles. [3] In this configuration, the X-ray tube rotates around the scintillator's center. Following the acquisition of 2D X-ray images at diverse angles, the distance-driven method is employed to acquire slice images of the object (Fig. 1.a). The finalized system is visually depicted in Fig. 1.b. To assess the resolution of the X-ray imaging system in conjunction with the optical lens, measurements were conducted. The Jima RT RC-04 resolution chart served as the basis for gauging the resolution of the sliced X-ray image (Fig. 2). The system successfully resolved the 2 and 3 μm resolution charts, whereas the 1 μm resolution chart could not be resolved.

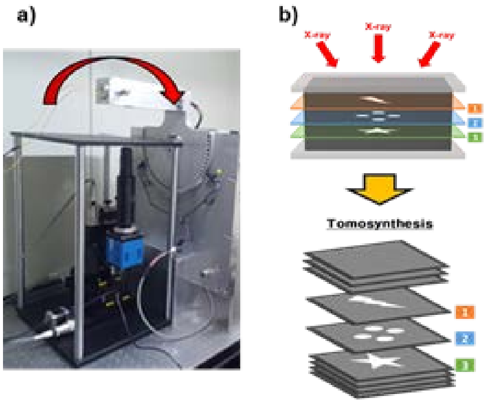

Fig. 1. a) Mechanism of X-ray micro-tomosynthesis, b) Developed X-ray micro-tomosynthesis system coupled with optical lens

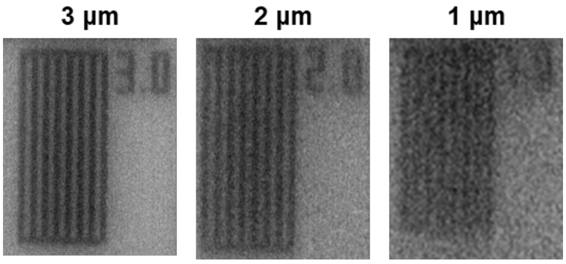

Fig. 2. Micro X-ray images of Jima RT RC-04 resolution chart

2.2 Super-Resolution Deep Learning

In the context of super-resolution deep learning, sub-micron resolution optical images were utilized as the training data. These optical images were captured under optical light conditions using the optical lens designed for optical-lens coupled X-ray imaging system. The training methodology is depicted in Fig. 3. To elaborate, the optical images undergo a down-sampling process using bi-cubic interpolation. Following this, Gaussian blurring kernels are convolved with the images and Gaussian noise is added. This procedure is aimed at generating optical images that closely resemble X-ray images. Subsequently, the resulting images are input into a neural network for the purpose of training.

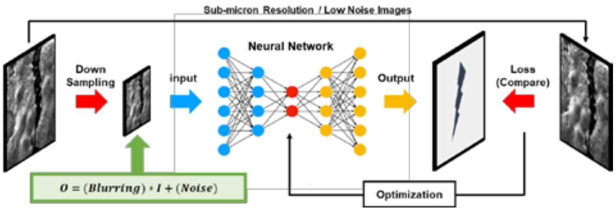

Fig. 3. Training method for super-resolution deep learning

The process of designing the blurring kernel is depicted in Fig. 4. The Edge Spread Function (ESF) is acquired from X-ray images of the tungsten metal and air interface using a purpose-built X-ray system. The ESF is then differentiated to calculate the Line Spread Function (LSF). By Gaussian fitting of the LSF, the standard deviation is determined. This standard deviation is subsequently utilized to create a Point Spread Function, serving as the Gaussian Blurring Kernel.

Regarding Gaussian noise, as illustrated in Fig. 5, the image distribution is extracted from the background of the sliced X-ray image. The standard deviation is computed by Gaussian fitting of this image distribution. Based on this calculated value, noise is introduced to the optical image.

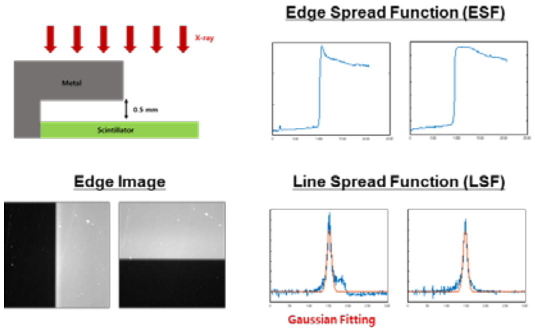

Fig. 4. Design method for Gaussian blurring kernel

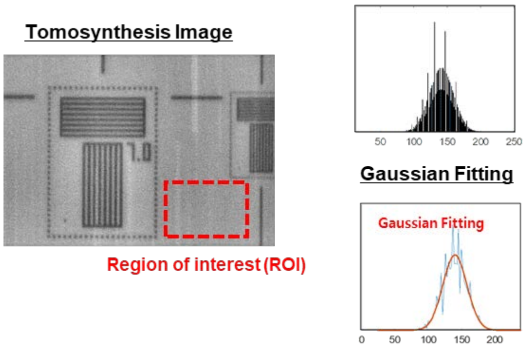

Fig. 5. Design method for Gaussian noise

In this study, the Very Deep Convolutional Networks (VDCN) were employed as the neural network. [4] Furthermore, trans-convolution was incorporated for super-resolution. The optimizer was AdamW and a learning rate of 0.001 was utilized.

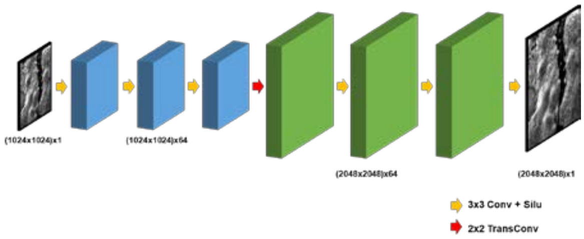

Fig. 6. VDCN with trans-convolution

The trained neural network was employed for forward propagation using sliced X-ray images reconstructed through tomosynthesis. The outcome of this process, depicted in Fig. 7, notably achieved successful resolution of the 1 μm resolution chart. This accomplishment serves as confirmation of achieving sub-micron resolution within the optical lens coupled X-ray imaging system, a domain that had previously been considered unattainable.

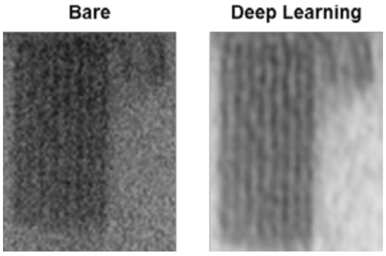

Fig. 6. 1 μm resolution chart (Jima RT RC-04), Tomosynthesis Image (Left), Tomosynthesis + Deep Learning (Right)

3. Conclusions

In this study, the application of deep learning to the optical-lens coupled X-ray imaging system successfully achieved sub-micron resolution X-ray imaging. This system retains the advantages of being cost-effective and compact compared to conventional micro-focus X-ray tube-based imaging systems while attaining sub-micron resolution. Consequently, this research can be considered highly significant.

The outcomes of this study have the potential to greatly contribute to various fields such as biology, NDT, and physics, where micro X-ray imaging is indispensable. This achievement is expected to provide valuable insights and aid in advancing numerous research endeavors.

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