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Development of wide one-dimensional X-ray line sensor in backscatter X-ray imaging system for infrastructure inspection

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We fabricated a wide one-dimensional X-ray line sensor in backscatter X-ray imaging system. The length and width of the sensitive area of our line sensor is 200 mm and 50 mm, respectively. By using fan-beam X-rays and scanning in the perpendicular direction to the fan-beam plane, two-dimensional backscatter X-ray images can be obtained. In basic experiments, we confirmed that an iron rod placed at the depth of, at least, 9 cm in a concrete block can be seen by combining our line sensor and C-band linac X-ray generator.

Keywords: wide one-dimensional X-ray line sensor; backscatter X-ray imaging; infrastructure inspection

1. Introduction

Routine inspections and maintenances for aged infrastructures, such as bridges and tunnels, are important. One of the methods of non-destructive inspections is X-ray imaging. The transmission X-ray imaging inspection is, however, not suitable for large structures because a huge object should be sandwiched between an X-ray source and a detector. In backscatter X-ray imaging technique, the both of the X-ray source and the detector are placed on one side of a specimen.

So far several techniques for backscatter X-ray imaging have been proposed and developed [1-5]. The most famous one is a pencil beam scanning technique. This is also called as a backscatter X-ray radiography by selective detection (RSD) [1,2]. This method, however, needs long acquisition time in order to obtain fine images. Another one is the snapshot aperture backscatter radiography (SABR) [3,4]. The detector used in this method is a computed radiography (CR) plate shielded from direct X-ray radiations by a lattice of lead tiles. X-rays illuminate the target object through apertures between the lead tiles and are backscattered toward the CR plate. This method can obtain images with relatively short acquisition time.

In order to inspect a deep region in a huge object, high-energy X-rays should be applied. The above two methods, however, are not suitable to use high-energy X-rays. In the RSD method, a huge collimator is required to collimate high-energy X-rays. It is difficult to scan with high speed. In the SABR method, the

shielding lead tiles should be thick to reduce penetration of high-energy X-rays. However, it is difficult to illuminate the target object through the gap between the thick tiles. This configuration is also not suitable to obtain fine images for the deep region. In order to apply high-energy X-rays in the backscatter X-ray imaging, we apply a novel method using fan-beam X-rays and a wide one-dimensional X-ray line sensor with a parallel-plate collimator. In this configuration, the fan-beam X-rays illuminate only one slice of the object and the collimated line sensor can determine the one-dimensional position in the slice. This method can measure one line at a time and obtain a two-dimensional image by scanning in the perpendicular direction to the fan-beam plane.

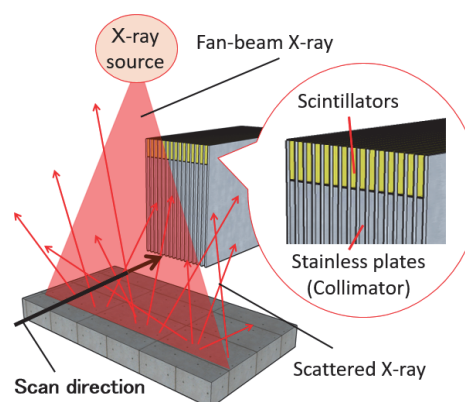


Figure 1. Conceptual drawing of the fan-beam scanning configuration of the backscatter X-ray imaging using a wide one-dimensional X-ray line sensor.

Figure 1 shows the conceptual drawing of this method. This fan-beam scanning method, which needs

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one-direction scanning, is faster and easier to scan a heavy collimator compared to the two-dimensional scanning of the pencil beam.

In this paper, we fabricate a wide one-dimensional X-ray line sensor for the backscatter X-ray imaging inspection. One of the features of our detector is to use a wide width line sensor, which allows to view a wide solid angle. We make basic experiments to check a proof-of-principle of our method and demonstrate to combine our detector with a high energy X-ray source. In addition, we roughly characterize inspection performance of the fabricated system.

2. Wide one-dimensional X-ray line sensor

The sensor consists of 100 sticks of cadmium tungstate (CdWO_4 , CWO) scintillators and the parallel plate collimator. Each CWO scintillator stick is sandwiched between the collimator plates. The dimension of the scintillator is 1 mm thick x 5 mm deep x 50 mm long. Each scintillator stick is wrapped with a Teflon tape as a reflector. The collimator plate is made of a stainless steel and its dimension is 0.5 mm thick x 80 mm wide x 80 mm long. The pitch of the scintillator sticks is consequently 2 mm. The length and width of the sensitive area of our line sensor is 200 mm and 50 mm, respectively.

Scintillation photons are collected from the $1 \times 5 \text{ mm}^2$ surfaces of the CWO scintillators. Optical-fiber light guides (Kuraray, CLEAR-PSMSJ) are connected to these surfaces to transmit scintillation photons. Opposite end surfaces of the optical fibers are bundled and arranged with equal spacing on the same plane. The scintillating pattern can be read out from the fiber end plane using a cooled CMOS camera (ANDOR, Neo 5.5). All the components are mounted in the ambient light shielding box. **Figure 2** shows the fabricated X-ray line sensor.

The images on the optical fiber end plane are transferred to the control computer and analyzed. The CMOS camera images often have white spots under X-ray irradiation. These spots are owing to direct impacts of X-rays into the CMOS elements. These spots can be rejected in the analyzing software. Consequently, backscatter X-ray line profiles or two-dimensional images

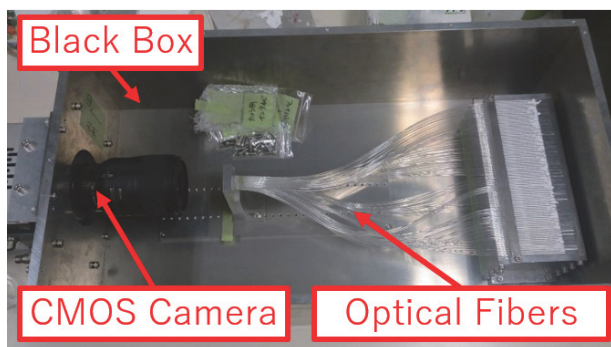


Figure 2. Photograph of the fabricated wide one-dimensional X-ray line sensor.

are reconstructed in the control computer.

3. Proof-of-principal experiments using a 450kV X-ray tube

In order to check a proof-of-principle of our method, the basic experiments were made using the fabricated line sensor and a 450 kV X-ray tube. **Figure 3** shows the experimental setup. X-rays emitted from the tube were shaped into a fan beam by a lead collimator. The thickness of the fan-beam X-ray was 30 mm on the target object. The scanning step was 10 mm. The X-ray tube current was 10 mA.

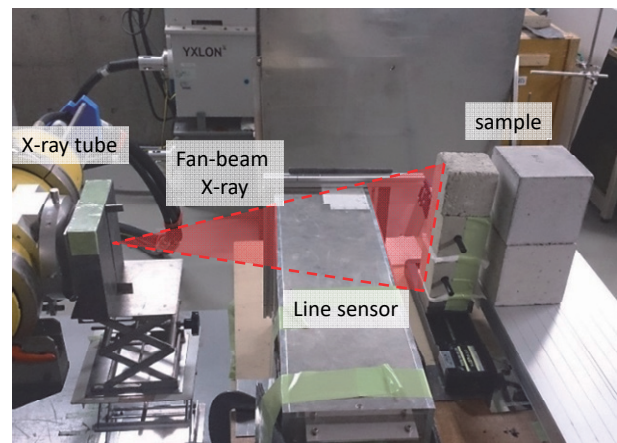


Figure 3. Experimental setup of the proof-of-principal experiments using a 450 kV X-ray tube.

Figure 4 shows the photographs of the target object. The target objects were concrete bricks, in which iron rods of 12 mm diameter are buried at the depths of 20 and 30 mm. The size of the bricks is $100 \times 100 \times 100 \text{ mm}^3$. The distance between the target object and the X-ray tube was roughly 650 mm. In practical cases, two-dimensional images can be obtained by scanning the fabricated line sensor and the X-ray tube. However, in this case, the target object was moved instead of the sensor and the tube. The scan area is indicated in **Figure 4**. A two-dimensional sample image obtained by our line sensor is also shown in **Figure 4**.

We can see both iron rods placed at the depths of 20 and 30 mm clearly. In addition, tiny gaps between the bricks can also be confirmed in the obtained image. Our system detects X-rays backscattered from a relatively deep region. If there is a shielding material at a relatively shallow region, irradiated X-rays decrease before reaching to the deep region. Therefore, the iron rods seem to be dark. On the other hand, if there is a void region, irradiated X-rays cannot be scattered. As a result, the tiny gaps also seem to be dark. Our inspection system is considered to have mm-order spatial resolution.

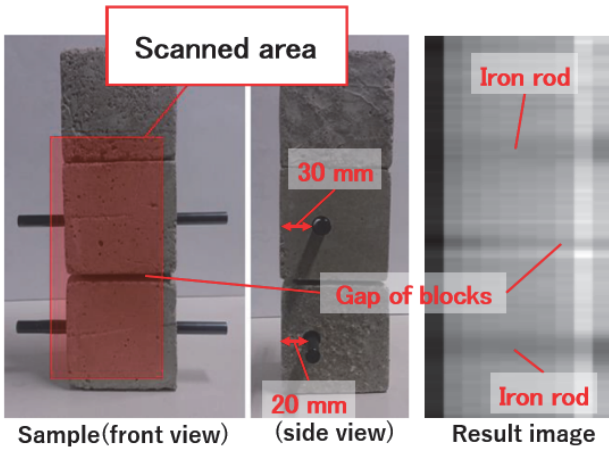


Figure 4. Photographs of the sample; (left) front view and (center) side view. (right) A two-dimensional sample image obtained by scanning the wide one-dimensional X-ray line sensor.

4. Experiments using a C-band linac X-ray generator

In order to visualize deep regions in large concrete objects, high-energy X-ray is required. We demonstrated to combine our sensor with a C-band linac X-ray generator, which emits 0.9 MeV bremsstrahlung X-ray. The electron linac based X-ray generator was developed by National Institute of Advanced Industrial Science and Technology (AIST), Japan. The target of the X-ray generator was made of tungsten. X-rays were shaped into a fan beam by the fan-beam shaping lead collimator. **Figure 5** shows the photograph of the C-band linac X-ray generator and the fan-beam shaping collimator

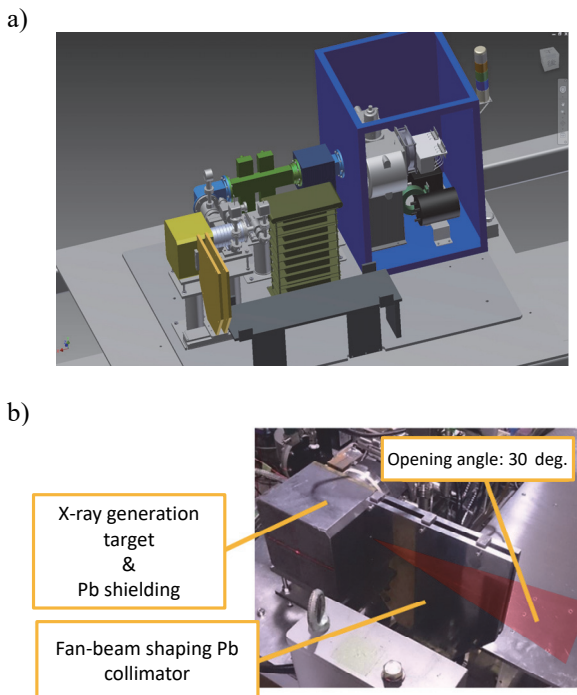


Figure 5. a) Drawing of the C-band linac X-ray generator. b) Photograph of the fan-beam shaping collimator and the X-ray generation target.

and the X-ray generation target. The opening angle of the fan beam was 30 degrees. The thickness of the fan beam was 15 mm on the sample surface.

The X-ray generator unit and our line sensor were mounted on a large linear stage to scan samples. As a demonstration, an adjustable wrench attached on the front surface of a concrete sample was measured. **Figure 6** shows the backscatter X-ray image of the adjustable wrench. In this image, the X-ray fan beam was vertically irradiated and horizontally scanned. The adjustable wrench shape can be recognized in the backscatter X-ray image. The concrete sample was formed by piling up several concrete bricks. A tiny gap between the concrete bricks was also seen. At the present, our system has a tendency to emphasize a tiny gap parallel to the fan-beam X-ray.

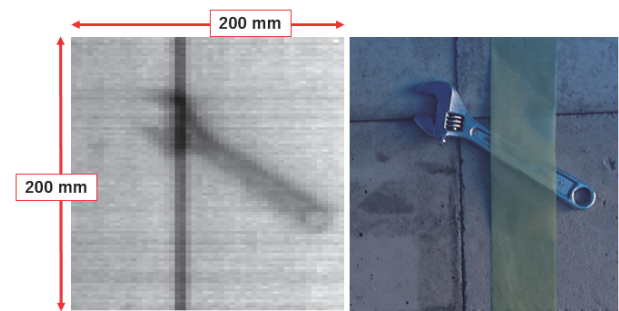


Figure 6. (left) Backscatter X-ray image and (right) photograph of an adjustable wrench attached on the front surface of the concrete sample. The concrete sample was formed by piling up several concrete bricks.

In order to evaluate performance of our backscatter X-ray imaging system, we measured the concrete sample, in which several iron rods were inserted at various depths. **Figure 7** shows the photograph and the schematic drawing of the concrete sample.

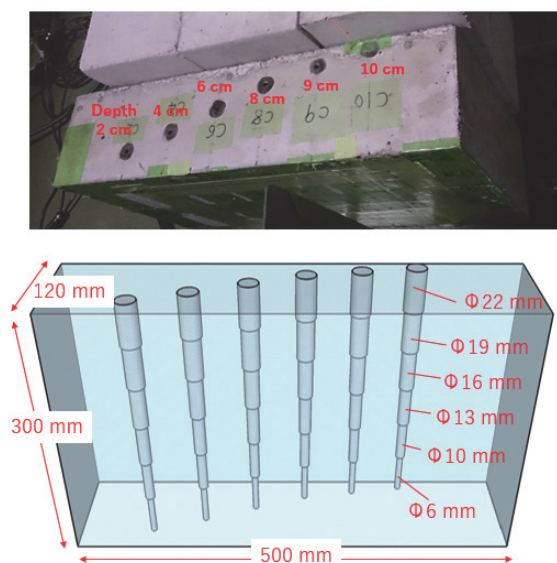


Figure 7. Photograph and schematic drawing of the concrete sample, in which several iron rods are inserted at various depths.

Figure 8 shows the backscatter X-ray image of the concrete sample. We can clearly see the iron rods at the depth of 6 cm in Figure 8. Iron rods placed at the depths of 8 and 9 cm is difficult to be recognized in this figure. In order to recognize these iron rods, we focused the deeper region.

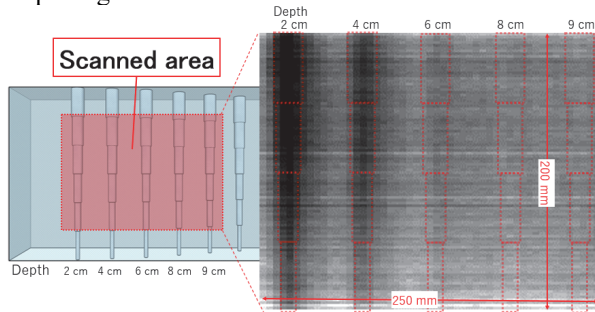


Figure 8. Backscatter X-ray image of the concrete sample shown in Figure 7.

Figure 9 shows the image obtained from the same sample as Figure 8 but the deeper region is focused. The horizontal profile vertically integrating image values is also shown in Figure 9. We can recognize the iron rod placed at the depth of 9 cm. We, therefore, conclude that our system can detect an iron rod placed at the depth of, at least, 9 cm in the concrete sample. Of course, although the deeper objects are desired to be seen, some objects, such as iron rods, are buried at the depth ranging from a few to ten cm in a concrete structure. Therefore, we consider that our system has minimum required performance.

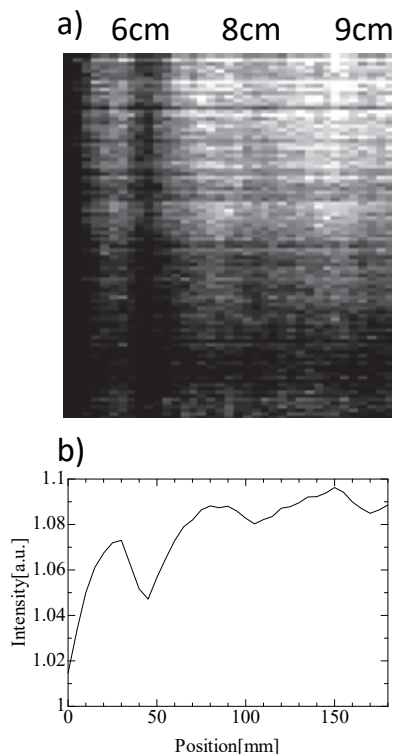


Figure 9. a) Backscatter X-ray image of the concrete sample shown in Figure 7. The iron rods placed in deeper region are focused. b) Horizontal profile integrating image values vertically.

At the present, the obtained images were disturbed by backscatter X-rays from a shallow region. In the conventional backscatter X-ray imaging technique, these scattering components are usually shielded. Our system is not optimized for shielding backscatter X-rays from a shallow region. If X-rays backscattered from the deeper region are shielded, the signal to noise ratio will be improved but the signal intensity will decrease. Therefore, we have to optimize geometrical arrangement of the shielding structures in our system. We expect that our system can see a deeper region by optimizing the shielding for backscatter X-rays from a shallow region.

5. Conclusions

We fabricated a wide one-dimensional X-ray line sensor for the backscatter X-ray imaging inspection. The length and the width of the sensitive area of the line sensor were 200 mm and 50 mm, respectively. The scintillation pattern was read out by the cooled CMOS camera through the optical fiber light guide. The direct impact events of high-energy X-rays to the CMOS camera can be rejected by the analyzing software.

Through basic experiments using high-energy X-ray generator, we demonstrated a proof-of-principle of our backscatter X-ray imaging method and confirmed that an iron rod placed at the depth of, at least, 9 cm in a concrete sample can be seen.

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References

- [1] B.C. Towe and A.M. Jacobs, X-Ray backscatter imaging, *IEEE Trans. on Biomed.-Engineering* BME-28 (1981), pp. 646-650.
- [2] E.T. Dugan, A.M. Jacobs, S.P. Keshavmurthy and J.C. Wehlburg, Lateral migration radiography, *Res. Nondestr. Eva.* 10 (1998), pp. 75-108.
- [3] A.M. Jacobs and E.T. Dugan, Snapshot backscatter radiography system and protocol, *Patent US 6,735,279 B1* (2004).
- [4] D. Shedlock, X-ray backscatter imaging for radiography by selective detection and snapshot: Evolution, development, and optimization, *Ph.D Thesis, University of Florida* (2007).
- [5] S. Kolkoori, N. Wrobel, U. Zscherpel and U. Ewert, A new X-ray backscatter imaging technique for non-destructive testing of aerospace materials, *NDT&E Int.* 70 (2015), pp. 41-52.