# Superiority of zoom lens coupling in designing a novel X-ray image detector

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We design a novel X-ray image detector by lens coupling a $Gd_2O_2S$:Tb intensifying screen with a high performance low-light-level ($L^3$, which often means luminescence less than $10^{-3}$ Lux) image intensifier. Different coupling effects on imaging performance between zoom lens and fix-focus lens are analyzed theoretically. In experiment, for designing a detector of 15-inch visual field, the system coupled by zoom lens is of 12.25-lp/cm resolution, while the one with fix-focus lens is 10 lp/cm. The superiority of zoom lens is validated. It is concluded that zoom lens preserves the image information better than fix-focus lens and improves the imaging system's performance in this design, which is referential to the design of other optical imaging systems.

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X-ray imaging technology has been greatly improved and widely applied in industrial detection since X-rays were discovered in 1895. The X-ray image intensifier we use, undoubtedly the key component in an X-ray imaging system, is mainly imported from France and Japan. However, for cost consideration, the X-ray image intensifier with 9-inch or larger visual field was seldom imported, which limits its application in large size object observation. For this reason, we design a novel X-ray image detector of low cost and big visual field by combining the X-ray imaging technology with the low-light-level ($L^3$, luminescence often less than $10^{-3}$ Lux) imaging technology. This detector's imaging performance can meet the industrial detection requirements[1].

The conventional X-ray image detector appeared in 1950s, and it converts X-ray photon into many visible light photons, thus reducing the dose to the person in observation or the person nearby. As shown in Fig. 1, the imported X-ray image intensifier is composed of several parts including input screen, photo-cathode, electronic-optical system (focusing and acceleration parts), output screen, and vacuuming pump. When X-ray passes through the object and arrives at the input screen, the object's X-ray image is formed. The photo-cathode converts this X-ray image into visible light image and then the image's brightness is intensified by the electronic-optical system. Finally, the visible light image with enough brightness appears on the output screen. The vacuuming pump preserves the tube in vacuum of $10^{-7}$ torr.

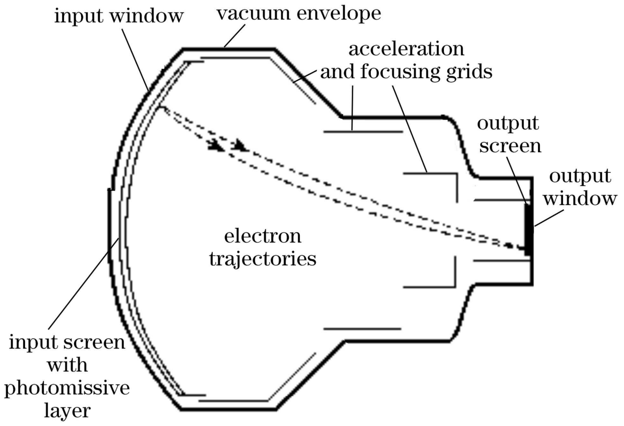

Fig. 1. Scheme of conventional X-ray image intensifier.

For comparison, the novel X-ray image detector designed by us is a combined system of an X-ray intensifying screen and a $L^3$ image intensifier (often used in military affairs), as shown in Fig. 2[2−4]. Because $L^3$ image intensifier is a vacuum device, while the X-ray intensifying screen is not, this novel detector is a vacuum-nonvacuum combination. Moreover, this combination is based on some other design principles detailedly introduced in Refs. [5,6].

When X-ray passes through the object and arrives at the X-ray intensifying screen, the object's visible light image is formed. Although the intensifying screen can convert one X-ray photon into many visible light photons, the image's brightness is still not high enough. Therefore,

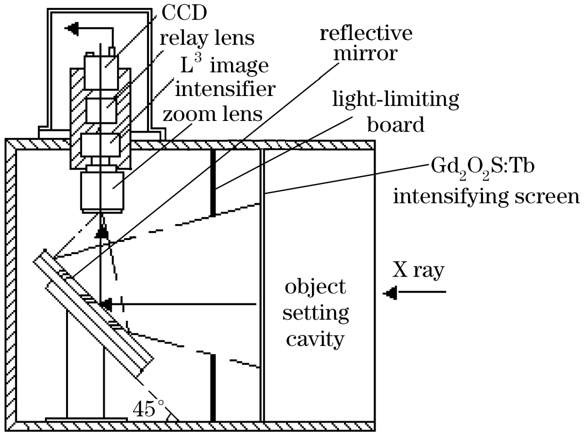

Fig. 2. Novel X-ray image intensifier and video system.

we use a $L^3$ image intensifier to make the visible light image brighter, and it can intensify the brightness up to $10^4$ times.

As is well known, the bigger visual field the conventional X-ray image detector has, more difficult its manufacturing technique is, so the detector with visual field bigger than 16 inch does seldom appear. In practice, a detector with 15-inch visual field is enough, so we design a detector in this size. When choosing a coupling lens for the X-ray intensifying screen[3] and the $L^3$ image intensifier[4], a fix-focus lens and a lens with 2.5 zoom ratio are considered. Zoom lens makes the imaging system's visual field variable in the range of $6-15$ inch[6−8], while system coupled by fix-focus lens changes the visual field by moving the object's position between the X-ray source and the detector. Except for this, zoom lens coupling can preserve more image information, which is given in detail below[7].

Figure 3 describes the geometric principles of X-ray imaging in usual industrial detection. We know that, if the detector's visual field is not enough, the object's image must be amplified for clear observation. As shown in Fig. 3, the object usually is placed somewhere between the X-ray source and the detector for image magnification. The magnification depends mainly on the object's geometric position and can be given by

$$M = \frac{a}{a_\mathrm{o}} = \frac{L_1 + L_2}{L_1} = 1 + \frac{L_2}{L_1}, \tag{1}$$

where $M$ denotes image magnification, $a_\mathrm{o}$ and $a$ denote the sizes of the object and its image size respectively, $L_1$ and $L_2$ denote the distances from the object to the X-ray source and to the detector respectively.

Figure 3 shows that, X-ray source's focal spot brings penumbra to object's image, which results in image information loss. This is named geometric unsharpness and marked as $U_\mathrm{g}$. It depends on both the focal spot size $d$ and image magnification $M$,

$$U_\mathrm{g} = \frac{dL_2}{L_1} = d(M-1). \tag{2}$$

It is clear that $U_\mathrm{g}$ increases with $M$, therefore, we hope $M$ is smaller for preserving more image information.

Here, we suppose there be no other unsharpness but the geometric unsharpness and the detector's fixed unsharpness. The detector's fixed unsharpness $U_i$ depends on the system's component performance and the geometric unsharpness $U_\mathrm{g}$ results from image magnification, so the imaging system's total image unsharpness can be written as

$$U^2 = U_i^2 + U_\mathrm{g}^2. \tag{3}$$

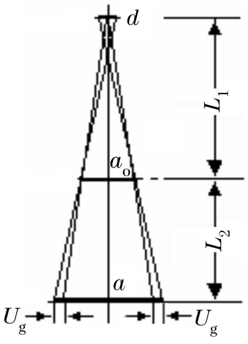

Fig. 3. Geometry principles of X-ray imaging.

However, the magnified image improves object observation effect by weakening the system's total image unsharpness, which can be presented as

$$U_\mathrm{o} = U/M, \tag{4}$$

where $U_\mathrm{o}$ denotes image's observing unsharpness. We hope $M$ is bigger because the less $U_\mathrm{o}$ is, the better the observation effect will be. But it conflicts with image information preserving. So it is necessary to find the tradeoff.

By combing Eqs. (2)—(4), we calculate the difference in $M$ and get the optimal magnification $M_\mathrm{opt}$:

$$M_\mathrm{opt} = 1 + (U_i/d)^2. \tag{5}$$

From Eq. (5), we can find the object's best position between the X-ray source and the X-ray image detector, which is the tradeoff between image observation effect and image information loss.

If a fix-focus lens is used, it will accord with the imaging principles above and the image magnification depends on object's relative position. But when zoom lens is used in the X-ray image detector, there must be much difference with the conventional one. In this case, the image magnification mainly depends on zoom lens' modulation.

In experiment, the X-ray source's focal spot is 0.8 mm in diameter, the $\mathrm{Gd_2O_2S{:}Tb}$ X-ray intensifying screen is of 70-lp/cm resolution, the coupling lens (zoom lens or fix-focus lens) is of 700-lp/cm resolution, the $L^3$ image intensifier is of 650-lp/cm resolution, and the last two are of $\phi$17.5 mm effective area. The image is delivered to a Cool SNAP of charge-coupled device (CCD). An example of designed detector with 15-inch visual field is given below for comparison in two kinds of lens coupling.

For the fix-focus lens coupling, according to imaging system's spatial resolution model $R^2 = \sum r^{2}$[8], the fixed unsharpness of the detector with 15-inch visual field is 0.44 mm. The other corresponding values can be calculated through Eqs. (2), (3) and (5):

$$M_\mathrm{opt} = 1 + (\frac{U_i}{d})^2 = 1 + (\frac{U_{15}}{d})^2 = 1 + (\frac{0.44}{0.8})^2 \approx 1.30,$$

$$U_\mathrm{g} = d(M-1) = 0.8 \times (1.30 - 1) = 0.24 \text{ (mm)},$$

$$U^2 = U_i^2 + U_\mathrm{g}^2 = U_{15}^2 + U_\mathrm{g}^2$$

$$= 0.44^2 + 0.24^2 \approx 0.50^2 \text{ (mm}^2\text{)}.$$

Because the relation between spatial resolution and total image unsharpenss is $R = 1/(2U)$, we can get that the corresponding spatial resolution is 10-lp/cm. So when we design a detector with 15-inch visual field, the image must be amplified in 11.54-inch (15-inch/1.30) visual field if a fix-focus lens is used.

For the zoom lens coupling method, we place the object on the detector's surface tightly. The image amplification only depends on the zoom lens' modulation, which avoids geometric unshapness resulting from X-ray source's focal

**Table 1. Coupling Comparison between Two Kinds of Lenses**

| $J$ (inch) | $M_{\mathrm{opt}}$ | $J'$ (inch) | $R_{\mathrm{f}}$ (lp/cm) | $R_{\mathrm{z}}$ (lp/cm) |
|---|---|---|---|---|
| 6 | 1.22 | 4.92 | 11.94 | 13.41 |
| 9 | 1.24 | 7.26 | 11.49 | 13.07 |
| 12 | 1.26 | 9.52 | 10.82 | 12.66 |
| 15 | 1.30 | 11.54 | 10.00 | 12.25 |

spot. For comparison, we zoomed in the image with the same magnification 1.30. According to the imaging system's spatial resolution model[8], the corresponding resolution value is 12.25-lp/cm. By the same method, other values for different visual fields can be got, as listed in Table 1. In Table 1, $J$ denotes the original visual field, $J'$ denotes the observation visual filed, $R_{\mathrm{f}}$ and $R_{\mathrm{z}}$denote corresponding system resolutions in different coupling methods.

Figure 4 shows the theoretical curves according to different visual fields. It is obvious that zoom lens coupling is superior. The system resolution decreases with visual field and this phenomenon is more obvious for fix-focus lens, because the resolution is restricted by visual field standard like the imported image intensifier[8].

To validate the theoretical analysis, we performed the experiment. Operation parameters are: homemade X-ray source with 0.8-mm focal spot; a computer with 512-MB memeory and Windows XP(SP2) operation system; Cool SNAP cf CCD of $10^6$ pixels; 70-kV working voltage and 3-mA current. Figure 5 shows the output images of two kinds of lens coupling methods. It is obvious that the result obtained by the zoom lens coupling is clearer, which is of 12-lp/cm resolution. This validates the theoretical values in Table 1.

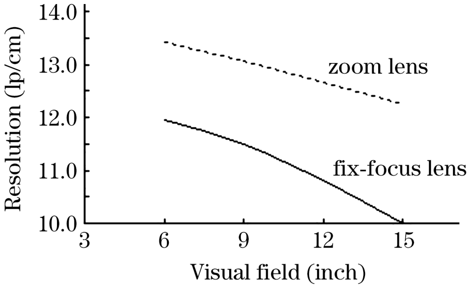

Fig. 4. Theoretical resolution.

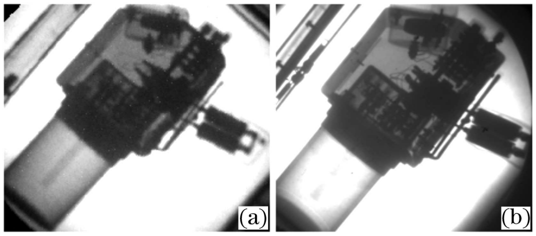

Fig. 5. Toolbox images obtained by (a) fix-focus lens coupling and (b) zoom lens coupling.

In conclusion, to design a novel X-ray image detector, zoom lens coupling is better than fix-focus lens. Modulating zoom lens makes visual field variable in some range, and thus makes it convenient to observe object. Zoom lens coupling is pivotal in this design, which improves the imaging performance and makes the system meet industrial detection requirement. This method is also referential to the design of other imaging systems.

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## References

1. C. Yu, T. Liu, L. Wu, and B. Chang, Proc. SPIE **5630,** 141 (2005).
2. C. Yu, B. Chang, S. Wang, and Q. Wang, Chin. Opt. Lett. **4,** 158 (2006).
3. Z. Zuo, Sensitization Materials (in Chinese) (3) 21 (2000).
4. W. Jin, G. Liu, X. Wang, Z. Wang, H. Sun, and L. Ding, Opt. Technique (in Chinese) **30,** 460 (2004).
5. C. Yu, B. Chang, and D. Wei, Rev. Sci. Instrum. **77,** 123102 (2006).
6. C. Yu, B. Chang, and D. Wei, J. Sci. Instrum. (in Chinese) **28,** 150 (2007).
7. S. Zheng, Nondestructive Testing (in Chinese) **28,** 222 (2006).
8. C. Yu, B. Chang, and D. Wei, Opto-Electron. Eng. (in Chinese) **33,** 120 (2006).