Real-time optical image subtraction and edge enhancement using ferroelectric liquid-crystal devices based on speckle modulation

Xin Lin, Junji Ohtsubo, and Tamiki Takemori

We carried out real-time optical image subtraction and edge enhancement based on a speckle modulation technique by using ferroelectric liquid-crystal polarization switches and a ferroelectric liquid-crystal spatial light modulator. A ferroelectric liquid-crystal spatial light modulator is employed as a real-time and multiple-exposure optical device, and successful results are obtained from three-exposure images modulated by speckles. Thus, image subtraction and edge enhancement are realized in real time. The whole operation is performed within several milliseconds with modest operating conditions. Because the spatial light modulator has a high resolution of greater than 100 line pairs/mm and can store fine speckle patterns, the image qualities we obtained are quite satisfactory. © 1996 Optical Society of America

1. Introduction

Optical image subtraction and other optical information processing based on the speckle modulation technique have been proposed since the early 1970's.1-3 The speckle modulation technique has also been applied to speckle metrology. As usual, an image to be processed has a rather low-frequency signal component and a small diffraction area in the Fourier plane. But with the introduction of speckle modulation, its information is forced to spread out into the high-frequency region. Thus, the technique makes it easier to filter a Fourier spectrum and process an input image. But the proposed methods were based on a photographic technique with which real-time processing is not possible. As an alternative method, a video system has been used for the processing, however, the resolution of the imaging device and the total number of pixels are currently not sufficient to obtain good results and processing is also limited by the video frame rate.

Optically addressable spatial light modulators are now readily available and are expected to be usable as rewritable real-time devices for optical information processing and optical computing. One of the promising devices is a ferroelectric liquid-crystal spatial light modulator [FLC SLM] that can be used in various fields of optical information processing such as real-time speckle metrology,4,5 real-time optical correlation,6 optical phase conjugation,7 real-time holography,8,9 and optoelectronic neural networks.10 The FLC SLM has attractive features of high sensitivity, high gain, fast response, multiple-exposure capability, and high resolution as a real-time optical SLM.

In this paper we propose a novel technique of real-time image subtraction and edge enhancement by using a FLC SLM and FLC polarization switches based on speckle modulation. In the proposed system we employed the FLC SLM as a real-time multiple-exposure device instead of a photographic plate. We also used FLC polarization switches together with birefringent plates to generate appropriate spatial offsets to realize image subtraction for the successive exposures. By using the same optical system as that for image subtraction, one can perform edge enhancement of an image by using successive exposures with focused and defocused imaging systems. The exposed pattern on the FLC SLM is optically Fourier transformed and filtered by a slit filter at the Fourier plane. Finally, the edge-enhanced image can be obtained by the optical
Fourier transform of filtered patterns. The FLC SLM can be switched as fast as microseconds, so that it is possible to perform image subtraction and edge enhancement within several to 10 μs at its fastest operation rate. Therefore, the potential operating speed is expected to be much faster than that of a conventional system. The actual switching speed of the FLC SLM is dependent on the incoming light level. Another advantage of the FLC SLM with the speckle modulation technique is that the FLC SLM can store high-frequency information because of its high-resolution image-capture capability.

2. Speckle Modulation for Image Subtraction and Edge Enhancement

A laser speckle pattern contains high spatial frequencies and can be used to carry image information by a random coding. The method of subtraction between images by speckle modulation using a photographic film or video devices has already been studied. In this paper we propose a faster image subtraction method by using real-time optical devices, and we briefly summarize the method of speckle modulation and image subtraction.

Consider two images A and B modulated by the same laser speckle pattern G. When the two images modulated by the speckle pattern at an x–y coordinate are exposed twice on a real-time imaging device, such as the FLC SLM used in this experiment, and we introduce a speckle translation \( y_0 \) in the y direction between successive exposures, the total intensity \( t(x, y) \) to be recorded can be written by

\[
t(x, y) = [a(x, y)g(x, y)] \ast \delta(x, y + \frac{y_0}{2}) + [b(x, y)g(x, y)] \ast \delta(x, y - \frac{y_0}{2})
\]

\[
= [a(x, y)g(x, y)] \ast \left[ \delta(x, y + \frac{y_0}{2}) + \delta(x, y - \frac{y_0}{2}) \right] \\
- [d(x, y)g(x, y)] \ast \delta(x, y - \frac{y_0}{2}),
\]

where \( d(x, y) = a(x, y) - b(x, y) \) is the difference between the two images, \( a(x, y) \) and \( b(x, y) \) are the functions that correspond to images A and B, respectively, and \( g(x, y) \) represents the speckle pattern. The asterisk denotes a convolution operator and \( \delta(\cdots) \) is the delta function. The optical Fourier transform of intensity \( t(x, y) \) is given by

\[
T(u, v) = 2[A(u, v) \ast G(u, v)] \cos \left( \frac{\pi uv}{\lambda} y_0 \right) \\
- [D(u, v) \ast G(u, v)] \exp \left( -i \frac{\pi uv}{\lambda} y_0 \right),
\]

where \( u, v \) is a Fourier coordinate, the uppercase letters represent the Fourier transforms of the corresponding lowercase letters, and \( \lambda \) is the wavelength of light. The first term of Eq. (2) is a fringe term produced by speckle translations. If the Fourier-transformed pattern is filtered and the information around the dark fringes, i.e., \( \cos(\pi uy_0/\lambda) \sim 0 \), passes through the filter, only the second term can be extracted, and the image subtraction can be obtained by an optical Fourier transform of the filtered pattern. If the speckles are fine enough in image space, Fourier function \( G(u, v) \) becomes a broadband function, and image subtraction \( D(u, v) \) can be fully extracted by the filtering.

The dark fringes produced by the two-exposure pattern are so narrow that the intensity level of the filtered pattern can scarcely be observed. Therefore, a three- or multiple-exposure technique is necessary to obtain a sufficient intensity level. In the proposed real-time image subtraction, we can demonstrate a three-exposure technique of the pattern by using the multiple-exposure capability of the FLC SLM. In the three-exposure procedure, first, the \( -y_0 \) spatial translation of the speckle pattern associated with image A is given for an exposure time \( t_0/2 \) and, then, image B modulated by the speckle pattern without translation is exposed for a duration of \( t_0/2 \). Finally, image A, modulated by the translated speckle pattern with \( y_0 \), is exposed for \( t_0/2 \). Then the recorded light intensity on the FLC SLM is given by

\[
t(x, y) = [a(x, y)g(x, y)] \ast \delta(x, y + \frac{y_0}{2}) + [b(x, y)g(x, y)] \ast \delta(x, y - \frac{y_0}{2}) \\
= [a(x, y)g(x, y)] \ast \left[ \delta(x, y + \frac{y_0}{2}) + \delta(x, y - \frac{y_0}{2}) \right] \\
- [d(x, y)g(x, y)] \ast \delta(x, y). \\
\]

The corresponding Fourier spectrum can be calculated as

\[
T(u, v) = 2[A(u, v) \ast G(u, v)] \cos \left( \frac{\pi uv}{\lambda} y_0 \right) \\
- [D(u, v) \ast G(u, v)].
\]

Fringe modulation is proportional to the square of the cosine term and the dark fringe parts are enlarged compared with those obtained with the two-exposure technique. The necessary information here is again only the difference of the two images, and it can be extracted for the negligibly small value of the first term in Eq. (4). With the three-exposure technique, unlike the two-exposure technique, we can use a wider slit to filter the Fourier pattern and obtain a good filtered image.

Real-time edge enhancement of an image can be conducted by use of the same principle as that for the proposed image subtraction. Consider the case that one of two images, say image B, is the same as image A, but the imaging system for \( B (=A) \) is defocused. The speckle patterns to be modulated are almost
Eq. (5) obtained by the Fourier transform of Eq. (4) can be rewritten as

\[ D(u, v) = A(u, v) (1 - H(u, v)) \]

where the function \( H(u, v) \) is the optical transfer function (OTF) for the defocused imaging system. For example, for a rectangular aperture it is given by

\[
H(u, v) = \Lambda \left( \frac{u}{2f_0} \right)^2 \left( \frac{v}{2f_0} \right)^2 \left[ \frac{w_0^4}{4} \left( 1 - \frac{u}{2f_0} \right)^2 \right] \left[ \sin \left( \frac{w_0^4}{4} \left( 1 - \frac{u}{2f_0} \right)^2 \right) \right] \cdot
\]

Here, \( \Lambda(\cdot \cdot) \) and \( \sin(\cdot \cdot) \) are triangle and sine functions, respectively, \( f_0 \) denotes the coherent cutoff frequency of the imaging system, and \( w \) represents the maximum path-length error. Figure 1 shows a one-dimensional plot of the OTF for various parameter values of \( w \). If the second factor, \( 1 - H(u, v) \) of Eq. (5), is approximated by \( |iku||ikv| \) \( \lambda \) being a certain constant), then an exact differentiated pattern of image \( A \), namely, the edge-enhanced image, would be obtained by the Fourier transform of Eq. (5). In actuality, for a rectangular aperture the second factor is not proportional to \( uw \) but rather to \( u^2w \) for a large amount of defocus. However, as seen from Fig. 1, the OTF for a large amount of defocus has a wide linear region and the second factor in Eq. (5) can be assumed as a low-pass filter. Thus, the proposed system behaves as an approximate edge enhancement system for the input image.

There are several edge enhancement techniques based on digital image processing. For example, unsharp masking is a similar edge enhancement technique that can be used to subtract an image from its blurred version in a digital computer. As has already been discussed, fast optical techniques for image edge enhancement are expected for many applications of image processing. The proposed system is a promising one for fast optical image edge enhancement.

3. Experiments

Figure 2 shows the whole optical setup for the image subtraction and edge enhancement system. The right half of the figure represents the write-in system for a three-exposure image and the left half is the read-out system of the exposed image and the optical filtering system. A ground glass plate is illuminated by a laser beam from a 50-mW He–Ne laser (Laser 1) at the 632.8-nm wavelength. The depolarization effect through a ground glass plate is usually small as long as its surface roughness is around or less than the optical wavelength and the transmitted light through the ground glass, i.e., the generated speckle pattern, is assumed to be linearly polarized. The speckle pattern is divided by a half-mirror \( [HM] \) and each pattern illuminates image \( A \) or \( B \) through lens \( L_1 \) \( (f = 100 \text{ mm}) \). Birefringent calcite \( (\text{CaCO}_3) \) plates \( \text{BP1 and BP2} \) are employed to give an appropriate spatial offset to the speckle pattern. Three FLC polarization switches \( \{\text{PS1, PS2, and PS3} \} \) with clear apertures of 12 mm are used to realize three exposures in real time. The polarization of an input light through the FLC switch can be rotated by 90° by a positive applied voltage to the FLC cell. The maximum switching speed of the FLC polarization switches is 50 μs.

Details of the real-time three-exposure technique are shown schematically in Fig. 3. It is noted that the propagation of light is from right to left in this figure. In Fig. 3(a), the linearly polarized speckle pattern passes through the FLC polarization switch \( \{\text{PS1} \} \) as a \( p \)-polarized pattern that is due to the negative applied voltage to the polarization switch. The \( p \)-polarized pattern is shifted by a birefringent plate \( \{\text{BP1} \} \) as an extraordinary ray. The amount of the shift depends on the length of the birefringent calcite crystal along the light transmission. In our experiment, the birefringent plate has a size of 20 mm \( \times 20 \text{ mm}^2 \) and the thickness of the crystal is 4.59 mm, which corresponds to a spatial shift of the extraordinary ray of 0.5 mm at the 632.8-nm wavelength. One of the shifted patterns that is divided by the half-mirror is fed to another birefringent plate \( \{\text{BP2} \} \) and also has an additional shift of 0.5 mm through it. The FLC polarization switch \( \{\text{PS2} \} \) is driven by a negative voltage at this time and the output speckle pattern is a \( p \)-polarized pattern. Then the speckle pattern is blocked out by polarizer \( P2 \) and image \( A \) is not written onto the FLC SLM. The other pattern passes through the polarization switch \( \{\text{PS3} \} \) driven by a negative voltage and the pattern through \( \text{PS3} \) is a \( p \)-polarized one. The speckle pattern passes through polarizer \( P3 \) and the product of the speckle pattern with image \( B \) is taken. Then, image \( B \) with the speckle pattern is exposed onto the FLC SLM for a duration of \( t_0 \). In the following, this speckle pattern is assumed to have
zeroshift on the FLC SLM. In Fig. 3(b) the p-polarized speckle pattern is switched to an s-polarized one by the positive applied voltage to polarization switch PS1. The switched ordinary-ray pattern is not shifted by birefringent plate BP1 but is multiplied by image A as shown in Fig. 3(b). Then, image A with the shifted speckle pattern (the amount of the shift is $y_0$) with respect to the first exposure pattern is exposed onto the FLC SLM for a duration of $t_0/2$. In the same manner, image A with a shifted speckle pattern (the shift of $y_0$) is also exposed onto the FLC SLM for a time duration of $t_0/2$ as shown in Fig. 3(c). Thus, one can take three exposures of the images by using the multiple-exposure capability of the FLC SLM.

Lenses L2 and L3 used in the experiments (see Fig. 2) have focal lengths of 100 mm and both magnifications of the imaging systems are unity, so that shift $y_0$ of the speckle pattern is 0.5 mm on the FLC SLM. The average speckle size of the FLC SLM is 25 µm, which is sufficiently larger than the spatial resolution of the FLC SLM. The images with unshifted and shifted speckles are exposed by the FLC SLM. The FLC SLM used here was developed by Nippon Telegraph and Telephone Co. and fabricated by Hamamatsu Photonics, K.K. The clear aperture of the FLC SLM is 20 mm $\times$ 20 mm $^2$ and the average light power of the FLC SLM that we used in our experiments was estimated to be several hundred microwatts per square centimeter. The spatial resolution of the FLC SLM was measured to be more than 100 line pairs/mm for these experimental conditions. The general operation characteristics and structures of FLC SLMs have been described in several papers; see, e.g., Refs. 13 and 14. The switching speed of a FLC SLM depends on the incoming light intensity, and the typical switching speed of the FLC SLM is less than 100 µs. One can operate the FLC SLM by synchronizing it with the FLC polarization switches under the control of a microcomputer.

A typical example of the driving voltages for the FLC SLM and the FLC polarization switches is shown in Fig. 4. Figure 4(a) is a trace of the voltage of two cycles for the FLC SLM. The modulation voltages both for the FLC SLM and the FLC polarization switches were 30 V at a peak-to-peak value with zero mean. In Fig. 4(a) an erase pulse to eliminate
the previous pattern that is due to the bistable characteristic of the device had typically a 4-ms duration. The write-in pulse duration for the first exposure with a positive applied voltage to the FLC SLM was $t_0 = 300 \mu s$ and the pulse durations for the second and third exposures were $t_0/2 = 150 \mu s$. Dead times of 800 $\mu$s among each pulse were introduced to adjust the operations of the FLC SLM and the FLC polarization switches. Figures 4(a)–4(d) show the driving voltages for the FLC polarization switches synchronized with the FLC SLM operation. The FLC polarization switches were not driven by square-wave signals but by specifically optimized waveforms to facilitate faster switching of the FLC material. Then the waveforms exhibit a $\pm15$-V switching transient that quickly decays at approximately 300 $\mu$s to a $\pm5$-V switching voltage as illustrated in Figs. 4(b)–4(d). For each write-in pulse of the FLC SLM, it can easily be recognized that the corresponding applied voltages of the polarization switches are consistent with the operations shown in Fig. 3. The total cycle time for the read–write process is within several milliseconds in this case, but it can be significantly shortened by the employment of higher intensities of the write-in and read-out beams.

After the third exposure, the three-exposure pattern was read by a collimated read-out light of a 10-mW He–Ne laser from Laser 2 as shown in Fig. 2. The read-out beam from Laser 2 was turned on by an acousto-optic modulator (AO) only at the reading operation to avoid unnecessary exposure to the FLC SLM. The three-exposure pattern was Fourier transformed by lens FT-L1 ($f = 400$ mm) and the fringe pattern produced by the three exposures was enlarged by an objective lens ($\times10$), which is not shown in Fig. 2. Typical fringe separations were 2.4 mm at the Fourier plane. A 1-mm-wide slit filter was placed at the Fourier plane to pass through a dark fringe. The filtered amplitude, which contains the image subtraction information as discussed in Section 2, was again optically Fourier transformed by lens FT-L2 ($f = 400$ mm). The resulting output pattern was imaged onto a screen and recorded by a CCD camera. Finally, the difference between the two-exposure image and the edge-enhanced image was displayed on a TV monitor. Operation of the system was controlled by a microcomputer.

4. Results and Discussions

Based on the proposed three-exposure technique, real-time image subtraction and edge enhancement were performed. At first, we compared the fringe patterns for two- and three-exposure images. A speckle pattern produced by a ground glass plate without input images (see Fig. 2) was used to write two- and three-exposure patterns on the FLC SLM. Figure 5 shows an example of the observed Fourier fringes for two- and three-exposure patterns taken by the system shown in Fig. 2. Of course, the proposed system can be used as a two-exposure system by appropriate drives and timings for the FLC SLM and FLC polarization switch voltages. In Fig. 5(a) the observed dark fringes for the two exposures are so narrow that we must use a fine slit to extract the required information. This results in an obscure and noisy filtered output image. On the other hand, the dark parts of the fringes are enlarged for the three-exposure case as shown in Fig. 5(b), and thus we can obtain a better filtered image. In this experiment, we used only a single-slit filter. Nevertheless, the intensity levels and image qualities of the obtained results were satisfactory because we used three exposures. But high-intensity and

![Fig. 4. Electrical signals that were used to drive the (a) FLC SLM, and (b)–(d) the FLC polarization switches.](image)

![Fig. 5. Examples of the Fourier fringes observed in this experimental system with speckle patterns only. Fringe patterns that were obtained with (a) two exposures, and (b) three exposures.](image)
better quality images can be obtained by the employment of a multiple-slit filter at the Fourier plane.

Figure 6 shows examples of image subtractions that were obtained with the proposed system. The two original input patterns are letters SLM and L, as shown in Figs. 6(a) and 6(b), respectively. The letter L in both patterns was imaged at exactly the same position on the FLC SLM. These letters were recorded on the FLC SLM with speckle patterns by the three-exposure technique as already discussed. The size of each letter was approximately 3 mm$^2$. The three-exposure pattern was optically Fourier transformed and filtered by the single-slit filter. Then the final output of the image subtraction was obtained by a Fourier transform of the filtered pattern and detected by the CCD camera as shown in Fig. 6(c). The pattern recorded by the CCD camera is digitized by 0–255 on a gray scale and the signal levels of characters S and M in Fig. 6(c) are from 140 to 150. The background noise level is 20 and the level for the residue of subtracted image L is around 50. The noise and residue are not visible in this figure because of the small dynamic range of the photocopy. The obtained result is satisfactory and the modulation effect from speckle grains is actually not visible because each speckle is so fine.

Figure 7 shows two examples of the results for the edge enhancement of images. Figure 7(a) shows two original input patterns and Fig. 7(b) shows the output patterns recorded by the CCD camera for the corresponding inputs. The maximum path-length error $w$ introduced to generate the defocused image is approximately $w = \lambda/2$, which was calculated from the aperture size of the imaging lens, $l = 40$ mm [in the actual experiment, the aperture is circular], and defocus of approximately 60 µm. The OTF curve for the maximum path-length error of $w = \lambda/2$ has already been plotted in Fig. 1. In this experiment the speckle patterns were shifted to the horizontal direction in the figure. In spite of the roughly approximate system response for the differentiation and the one-dimensional shift of the speckle patterns, the obtained results are quite satisfactory and the speckle grain effect is scarcely observed in the edge-enhanced images.

Real-time image subtraction and edge enhancement are extremely important in optical associative memory and other image processing. Recently, real-time image subtraction that uses the polarization modulation of LCTV SLM’s has been proposed. But twisted-nematic liquid crystals used for LCTV SLM’s have a slow response time and can be operated at most by a video frame rate. However, the operation speed of our proposed system is faster than 10 ms with the modest operations of FLC devices, and the potential speed of ferroelectric crystal devices is 2 or 3 times faster than that of twisted-nematic crystal devices. Several methods exist that can be used to perform real-time optical edge enhancement of an image. For example, a high-pass filter in an optical filtering system can be used to obtain an edge-enhanced image. But, in this case, the intensity level of the resulting image is low because of the cut-off of the dc component. Therefore, a phase filter that blocks around the zero-order diffraction spot can sometimes be used as an approximate high-pass filter to obtain a high-intensity image. Another example is the method that utilizes real-time optical materials such as a specially designed edge enhancing SLM and photorefractive crystals. However, a high-power laser source is usually necessary for the system to operate and only...
a small portion of the input light power can be used as the output. In addition, a careful adjustment is required for the arrangement of such optical systems, although the optical arrangement is not so difficult, and the high output power efficiency can be attained by the use of a multiple-slit filter.

5. Conclusion
We have described real-time optical image subtraction and edge enhancement by using FLC devices based on the speckle modulation technique and have successfully realized real-time high-speed image subtraction and edge enhancement. The spatial shifts for a speckle pattern have been easily obtained with optical components that consist of a combination of FLC polarization switches and birefringent plates, and multiple-exposure images through a focused or defocused imaging system have been written onto a FLC SLM. The subtracted and edge-enhanced images have been successfully obtained from these multiple-exposure patterns by Fourier filtering. There are several methods for real-time image subtraction and edge enhancement; however, our proposed method has some advantages over the previous methods as discussed in Section 4.

FLC devices have the attractive features of high-speed switching, multiple exposures, and polarization and intensity switching capabilities, and they most certainly can become promising devices for real-time optical information processing and optical computing. One of the drawbacks of currently available FLC SLM’s may be their sensitivity to write-in intensity. This point should be improved to realize a faster, compact, and small-power laser system.

The authors thank T. Kurokawa for the use of the FLC SLM.

References