ON-AXIS COHERENT OPTICAL FEEDBACK SYSTEM FOR IMAGE PROCESSING

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Abstract

Coherent optical feedback systems always use a pair of tilted mirrors that physically separate the forward path and the feedback path, one of which is at an off-axis position. This paper introduces an on-axis configuration with two parallel mirrors. The application of the system to contrast enhancement and image restoration is presented.

Introduction

Both dc amplifiers and cameras process electromagnetic waves. The two systems have a common objective: to reproduce the input with linearity or with the desired nonlinearity. The difference between the two is that one has a feedback loop but the other does not. The feedback concept is indispensable for designing electrical analog systems, although it has not been used in imaging systems until recently. The reason is not because imaging systems have a special character that prevents use of the feedback concept but simply because the ratio of the wavelength to the size of the circuit differs substantially from that of the amplifier. For example, if a 5-kHz (λ = 60 km) voice is processed in a dc amplifier that has a 1-m-long feedback loop, then the ratio is 60,000:1. On the other hand if we use an optical wave (λ = 0.5 μm) in an optical feedback system of the same size, the ratio is 0.0000005:1. Thus it is unlikely that there will be any appreciable cross correlation when the output is fed back to the input. Hence, adding the two does not provide a meaningful result. This fact, however, does not suggest that we abandon the feedback concept, but rather that we use a light source with long temporal coherency and a micro-adjustable mechanism.

One way to create a feedback loop is to use a pair of tilted mirrors and lenses as shown in Fig. 1.(1) The origins of the Fourier plane are physically separated. We can place an appropriate filter G in the forward path and a filter H in the feedback path to improve the output. Some applications of this off-axis system to image processing have been reported.(1) In this paper we discuss the specific case when the tilt of the mirror is zero.

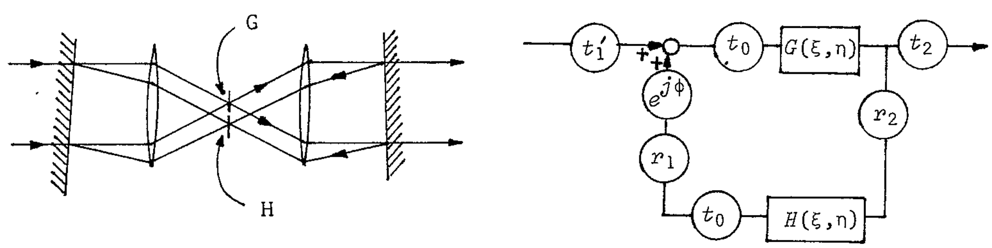


Fig. 1. Off-axis feedback system.

On-Axis Feedback System

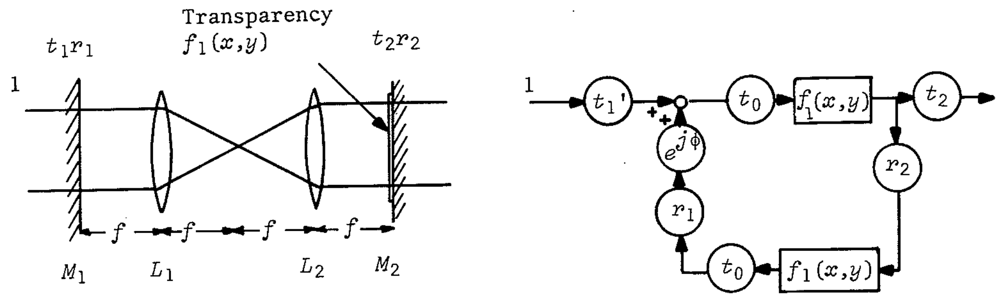
When the tilt of the mirror is zero, the mirrors are parallel to each other, the forward path and the feedback path are identical, and the two Fourier planes are not physically separable. The forward path filter also automatically acts as the feedback path filter. Thus we lose some degrees of freedom. However, this on-axis system has some essential merits such as easy alignment, smaller aberration, an unobstructed wide space in which to place the filter, and the capability for image processing. In some aspects we can expect superior performance from the on-axis system than from the off-axis one in spite of its smaller degrees of freedom.

Contrast Enhancement

An on-axis optical feedback system and its block diagram are shown in Fig. 2. A pair of lenses image one mirror onto the other. A transparency with amplitude transmittance distribution $f_0(x,y)$ is placed in a liquid gate, which is placed immediately before the second mirror. We introduce a unit amplitude plane wave to obtain the output amplitude distribution $f_1(x,y)$

$$f_1(x,y) = \frac{t_0 t_1' t_2 f_0(x,y)}{1 - t_0^2 r_1 r_2\, e^{j\phi}\, f_0^2(x,y)} \qquad (1)$$

where t_0, t_1', t_2 are the amplitude transmittances of the optics in the cavity, the first mirror, and the



(a) Physical configuration (b) Block diagram

Fig. 2. On-axis feedback system for contrast enhancement.

second mirror, r_1 and r_2 are the amplitude reflectance of the first and the second mirror, and ϕ is the phase introduced into the feedback signal.

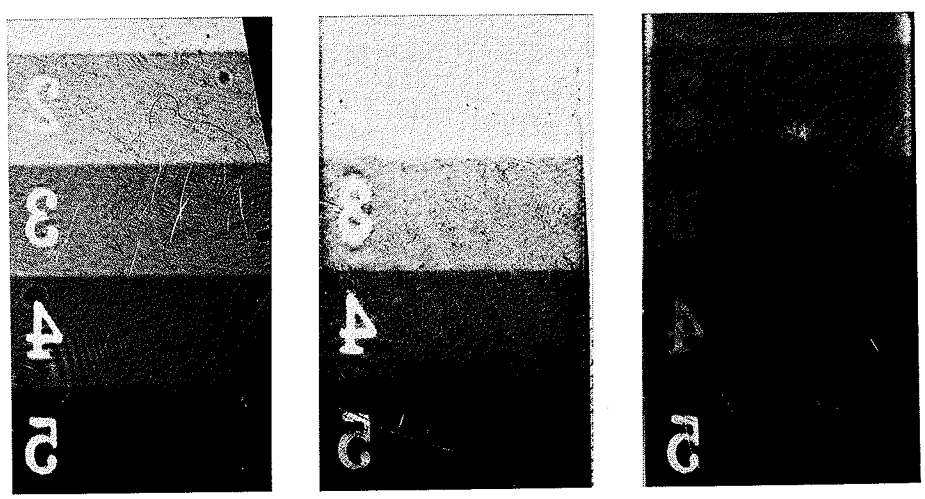
If the two mirrors have the same optical characteristics, we can simplify Eq. (1) to

$$f_1(x,y) = \frac{t_0 \mathscr{T} f_0(x,y)}{1 - t_0^2 \mathscr{R} e^{j\phi} f_0^2(x,y)} \tag{2}$$

where $\mathscr{T}$ and $\mathscr{R}$ are the intensity transmittance and the intensity reflectance of the mirror, respectively. We can change the phase ϕ by moving one of the mirrors with the aid of a piezoelectric transducer. The extreme cases can be observed when we set $\phi = 0$ or π

$$|f_1(x,y)|^2 = \frac{t_0^2 \mathscr{T}^2 f_0^2(x,y)}{[1 \pm t_0^2 \mathscr{R} e^{j\phi} f_0^2(x,y)]^2} \text{, negative when } \phi = 0\text{, positive when } \phi = \pi. \tag{3}$$

The relation between the transmittance of the transparency f_0^2 and the output f_1^2 is nonlinear. An experimental result using a step wedge is shown in Fig. 3 and plotted against a theoretical curve by Eq. (3) in Fig. 4. Notice that the phase variation changes the slope of the curve. Consequently, the contrast of the picture is higher or lower than the original.



(a) Original (b) $\phi = 0$ (c) $\phi = \pi$

Fig. 3. Increase and decrease of contrast.

The contrast enhancement effect due to the off-axis feedback system(1) is also plotted for comparison. It shows that the on-axis method has a wider range of contrast. We can choose the contrast between the two extremes by introducing the phase ϕ between 0 and π. This operation is done in real time since we can change the contrast as we observe.

The drawback of the feedback system is that it is difficult to process a transparency larger than 2 cm × 2 cm because of the aberration of the lenses, and it is hard to keep a uniform phase distribution across the field. Also, a liquid gate is necessary to cut the scattering on the surface of the emulsion and to reduce the optical path variation through the emulsion.

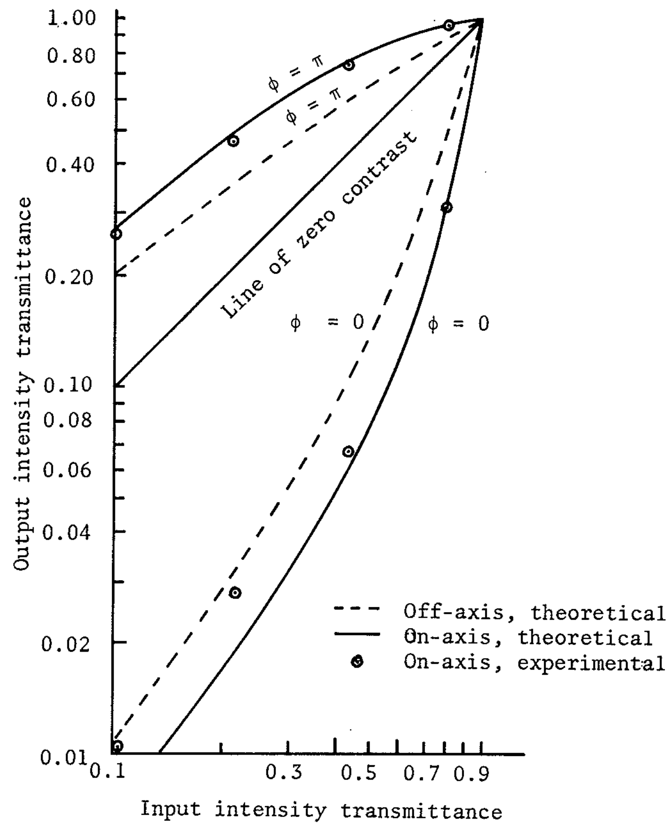


Fig. 4. Contrast change by feedback. ($t_0{}^2 = 0.84$, $\mathscr{R} = 0.9$).

Image Restoration

Here we examine an application of the system to image restoration. The physical configuration and the block diagram are given in Fig. 5. We image the input $f_1(x,y)$ on the first mirror. The beam goes through the same filter $G(\xi,\eta)$ in the forward path and the feedback path and we observe the leakage $f_2(x,y)$ through the second mirror on the screen. The transfer function of the feedback is given by

$$T(\xi,\eta) = \frac{t_0 \mathscr{T} G(\xi,\eta)}{1 - t_0{}^2 \mathscr{R} e^{j\phi} G^2(\xi,\eta)} . \tag{4}$$

Let $K(\xi,\eta)$ be the coherent transfer function of a specific imaging system, assuming K is real and varies from -1 to 1. We obtain a blurred image of $f_0(x,y)$ due to the amplitude attenuation of some frequency component. We input this blurred image to the on-axis feedback system and try to restore the original image by choosing an appropriate filter $G(\xi,\eta)$

$$K(\xi,\eta)T(\xi,\eta) = c$$

where c is a constant. Thus the filter $G(\xi,\eta)$ must satisfy

$$\frac{t_0 \mathscr{T} G(\xi,\eta) K(\xi,\eta)}{1 - t_0{}^2 \mathscr{R} e^{j\phi} G^2(\xi,\eta)} = c. \tag{5}$$

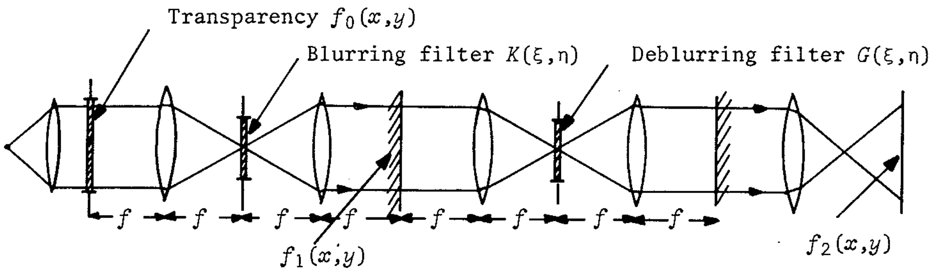
Set $\phi = \pi$. If $t_0{}^2 \mathscr{R} \simeq 1$, we can simplify Eq. (5) to

$$\frac{G(\xi,\eta)K(\xi,\eta)}{1 + G^2(\xi,\eta)} = \frac{1}{c'} , \tag{6}$$

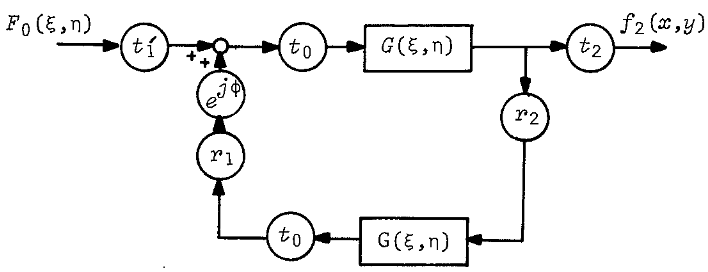
where

$$c' = \frac{c}{t_0 \mathscr{T}}$$

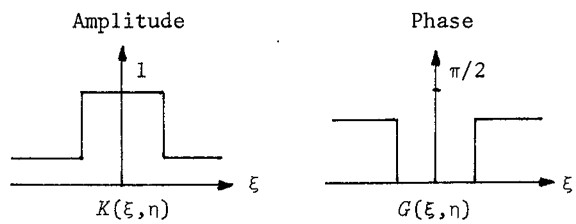
or



(a) Physical configuration.



(b) Block diagram.



(c) Blurring filter and corresponding deblurring filter.

Fig. 5. On-axis feedback system for image restoration.

$$G(\xi,\eta) = \frac{c'}{2} K(\xi,\eta) \pm [K^2(\xi,\eta) - (2/c')^2]^{\frac{1}{2}} . \tag{7}$$

If we choose $c' = 2$, then

$$G(\xi,\eta) = K(\xi,\eta) \pm j[1 - K^2(\xi,\eta)]^{\frac{1}{2}}. \tag{8}$$

On the other hand, we can express the complex amplitude transmittance $G(\xi,\eta)$ in the form

$$G(\xi,\eta) = A(\xi,\eta)\, e^{j\psi(\xi,\eta)}. \tag{9}$$

From Eq. (8) and Eq. (9) we have

$$A(\cos\psi + j\sin\psi) = K \pm j(1 - K^2)^{\frac{1}{2}}. \tag{10}$$

Hence

$$\begin{aligned} A(\xi,\eta) &= 1 \\ \psi(\xi,\eta) &= \cos^{-1}[K(\xi,\eta)] \end{aligned} \tag{11}$$

This indicates that the image restoration filter for K is a pure phase mask without absorption (Fig. 6). This eliminates the restriction due to the dynamic range of the filter, which is unavoidable in conventional inverse filtering methods. The restrictions come instead from the absorption of the optics and the mirrors.

An experimental transfer function and the corresponding phase mask are depicted in Fig. 5c. A three-bar target $f_0(x,y)$ is placed in the first object plane and the image $f_2(x,y)$ is recorded under different conditions (Fig. 7): (a) Without any filter and without the second mirror. (b) With filter K in place. The image is blurred in the x direction. (c) With phase mask G in place. The image is blurred to a further extent. This is due to the overall forward transfer function KG. (d) The second mirror is placed so that a feedback loop is created. Notice that the resolution is improved from the previous case but fails to exceed (b), which is our goal. This is due to the imperfect fabrication of the phase mask. The scattering and the absorption in the plateau part of the mask affect the high frequency part in the Fourier transform domain where we must maintain the higher gain to restore the image.

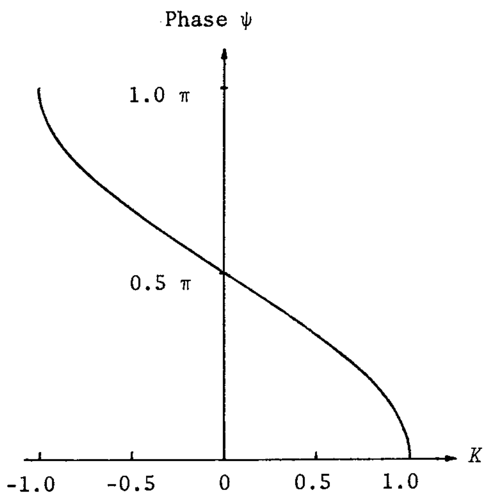
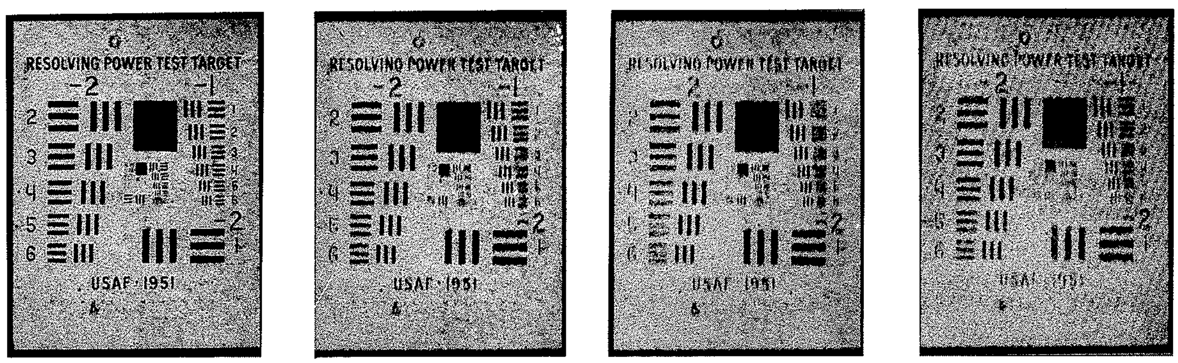


Fig. 6. Phase to be advanced by filter G.



(a) Original

(b) Blurred by *K*

(c) Blurred by *KG*

(d) Feedback applied

Fig. 7. Effect of the blurring filter and feedback.

Summary

The transfer function of the on-axis feedback system has been derived. The capability of increasing or decreasing the contrast of the input image is in agreement with the experimental data. Theoretical comparison indicates that higher and lower contrasts are attainable with the on-axis system than with the off-axis system.

Application of the same system to the image restoration was attempted. Analysis reveals that a pure phase mask is needed to restore the image, which is blurred by a real coherent transfer function, instead of an amplitude attenuator used in conventional inverse filtering. This eliminates the dynamic range problem of the filter usually encountered in image restoration techniques. Experimental results illustrate the ability of the system to perform image restoration. However, an improved phase mask must be fabricated to obtain the full potential of the system.

References

1. Lee, Sing H., "Mathematical Operations by Optical Processing," Optical Engineering, May/June 1974.