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RESTORATION AND ANALYSIS OF AMATEUR MOVIES FROM THE KENNEDY ASSASSINATION*

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ABSTRACT

Much of the evidence concerning the assassination of President Kennedy comes from amateur movies of the presidential motorcade. Two of the most revealing movies are those taken by the photographers Zapruder and Nix. Approximately 180 frames of the Zapruder film clearly show the general relation of persons in the presidential limousine. Many of the frames of interest were blurred by focus problems or by linear motion. The method of cepstral analysis was used to quantitatively measure the blur, followed by maximum a posteriori (MAP) restoration. We give descriptions of these methods complete with before-and-after examples from selected frames. The frames, which we analyzed in this manner, were then available for studies of facial expressions, hand motions, etc.

Numerous allegations charge that multiple gunmen played a role in an assassination plot. Multispectral analyses, adapted from studies of satellite imagery, show no evidence of an alleged rifle in the Zapruder film. Lastly, we use frame-averaging to reduce the noise in the Nix movie prior to MAP restoration. The restoration of the reduced-noise average frame more clearly shows that a least one of the alleged gunmen is only the light-and-shadow pattern beneath the trees.

INTRODUCTION AND SIGNIFICANCE OF WORK

A large fraction of the available evidence from the assassination of President Kennedy is in the form of photographs. Much of the photography of the fatal motorcade was made with amateur equipment of inadequate quality for the later assassination investigations. The staff of the Digital Signal and Image Analysis Group at the Los Alamos Scientific Laboratory (LASL) was part of a multi-laboratory team involved in digital restoration, enhancement, and analysis of selected images. At Los Alamos, we concentrated on significant frames from the 8-mm movies made by the photographers Zapruder and Nix.

The selected frames were chosen for relevance to questions of multiple shots and multiple gunmen. The Zapruder film shows the passengers in the presidential limousine through the fateful seconds from well before the first shot to well

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after the fatal shot. Assassination investigators have studied this film in detail for evidence of sudden changes in position, facial expressions, and general body position that might indicate multiple shots or an awareness by any limousine occupant that a shot had been fired. In a few Zapruder frames, there was the possibility that a second gunman was visible. The Nix film is of interest primarily because it shows a region of trees, lawn and architectural structures (the grassy knoll) in which some persons have claimed to see a second gunman.

The Zapruder film is now badly faded. Because of its archival value, we digitized a temporal sequence of approximately 180 frames for retention in the National Archives as digital images on magnetic tape. In this form, on archival quality tape, the images will deteriorate much less rapidly than the original film or conventional photographic copies. Further, the archive's staff can have unlimited numbers of digital copies made for historical study with no degradation of data. The original Zapruder film now has two missing sets of frames. For archival purposes, we also digitized first generation copies of the missing frames. The archival tapes will thus represent the best complete sequence of Zapruder images in existence.

We used the digitized images for several purposes at Los Alamos. All results were also available to other persons associated with the Photographic Evidence Panel. By far the bulk of our effort concentrated on generally sharpening poor imagery, i.e., image restoration. However, we also studied an individual Zapruder frame in detail (Frame 413). In this frame some observers claim to see a second gunman long after the fatal shot. This frame was subjected to color analysis for evidence of a rifle and to careful mensuration for location of the person whose head appears in the frame.

FILM DIGITIZATION ACTIVITIES

Often we view film digitization as a subdivision of the film into a checkerboard pattern followed by the measurement of average photographic density over each square. The "digital image" is then an ordered string of average density values. There is no reason, however, why we must restric our thinking to a checkerboard of contiguous samples. In the digitizations undertaken for the assassination study we determined that superior representations of the image would be obtained with "checkerboard squares" which overlapped.

The choice of parameters for the scan was a combination of theory and practical considerations. Two papers in the published literature treat the theory of scanning with finite-size apertures.[1,2] From those papers we know that if the center-to-center sample spacing is sufficiently small compared to image features, then the aperture size can be used to control noise in the scanned image.

A specification of image-feature size can be stated in term of spatial frequencies. We then determine the minimum sample spacing by the well-known Nyquist relation. Zapruder and Nix both used Kodachrome II film, stated by the manufacturer to have a resolution of 125 lines/mm under optimum conditions. However, for the low contrast and generally poor condition and quality of the Zapruder film, a maximum frequency of 50 lines/mm was generous. Based upon this estimate, which was shared by other consultants to the Photographic Panel, we selected a sample spacing of 10 microns.

The scanning aperture size can then be used to control the signal-to-noise ratio. In our work, an aperture as small as the sample spacing permitted such a small amount of light to pass through the microdensitometer that the instrument was difficult to calibrate and gave an electrically noisy signal. Enlarging the aperture mitigated these problems as well as reduced the effects of film grain noise. Based on these considerations we selected a scanning aperture of 15 microns.

Thus, we scanned the films with a 10-μ sample spacing and a 15-μ aperture. Three scans were made of each film, through Kodak Wratten Filter Types 92, 93, and 94, for color separation. The scanned image was reconstructed at the University of Southern California and shown to members of the Photographic Panel. That panel agreed that all information available in a first-generation copy of the original Zapruder film was also in the digitized image. A similar scanning recipe was applied to the Nix film at the Aerospace Corporation. The data tapes containing this information were sent to LASL.

IMAGE RESTORATION

Much of the information potentially available on the Zapruder and Nix films requires that the images be restored, i.e., changed to the quality which they would have had if the camera or photographic conditions had been better. Restoration is a two-step process:

a) Quantitative determination of the image defects that we intend to remove;
b) Removal of the defects with a numerical scheme.

The following two subsections treat these two steps. Then, in a final subsection we describe typical restoration activities.

Defect Determination

Many of the Zapruder frames are visibly blurred, apparently by camera motion or by motion of the film in and out of the focal plane as it advanced through the camera. Of course, we had no detailed knowledge beyond the image itself with which to quantitatively describe these defects. Recent work has shown[3] that these two common blurs, motion and defocus, embed telltale signatures in the blurred picture. Proper analysis allows the severity of these blurs to be determined from the image.

Both motion blur and defocus blur destroy information in the photographed scene. This loss of information occurs because these blurs have zeros in their frequency-domain transfer functions. In the case of linear motion blur or an out-of-focus lens, these zeros occur in a periodic pattern. While it is sometimes possible to detect these patterns by eye in the frequency domain, the presence of noise and near-random image information usually make this approach difficult. The periodic zero pattern can be made more visible through an averaging scheme that is used in power spectrum estimation. An unusually good example of zero location is shown in Fig. 1a, which was computed from an out-of-focus photograph. A more typical example, however, is shown in Fig. 1b, where the zeros are obscured by noise.

It has been shown[3] that even in the more difficult case of Fig. 1b, the pattern of zeros can be identified and used to determine blur severity. This is done by computing the power cepstrum of the picture. The power cepstrum is defined as the Fourier transform of the logarithm of the power spectrum. In the power cepstrum domain the circularly symmetric zero pattern of a defocus lens shows up as a ring of spikes. The zeros of a motion blur are denoted by peaks that identify both the direction and extent of the motion.

The mathematics involved in computing the power cepstrum are straightforward. The image formation system is denoted by

$$g(x,y) = f(x,y)*h(x,y) + n(x,y) \quad , \qquad (1)$$

where g is the blurred image, f the original image, h the spatially invariant blur, and n the noise. The power spectrum is computed using the method proposed by Welch[4,3] and results in

$$\Phi_g(u,v) = \Phi_f(u,v)\,|h(u,v)|^2 + \Phi_n(u,v) \quad , \qquad (2)$$

where Φ denotes the power spectrum of the signal indicated by the subscript. The power cepstrum is defined to be

$$P_g(p,q) = F\{\log \Phi_g(u,v)\} \quad , \qquad (3)$$

where $F\{\ \}$ denotes the Fourier transform. It is in the power cepstrum that the telltale spikes from motion or defocus blur can be readily identified. Figure 2a shows the cepstrum of a motion-blurred picture. The spacing and orientation of the peaks gives the extent and direction of the motion. Figure 2b is the cepstrum of an out-of-focus picture. Figure 2c shows an overhead view of the cepstrum of Fig. 2b in which the ring of spikes is related to the extent of defocus.

The numerical description of the image defect becomes the point spread function (PSF) or blurring matrix that we shall remove numerically.

Defect Removal

The model for image formation using photographic film that we use in this exercise is given by

$$g = s(h * f) + n$$

where

- g is the recorded image;
- f is the original image;
- h is a blurring matrix (point spread function);
- n is signal independent uncorrelated noise;
- s is a function representing the nonlinear film response. (This function was ignored above, but now becomes important.)

The deblurring method used here was nonlinear maximum a posteriori (MAP) restoration.[5] This scheme attempts to maximize the posterior probability, $p(f|g)$, given assumptions of the prior probabilities $p(f)$ and $p(g|f) = p(n)$. The algorithm is iterative in the spatial domain. It starts with a first guess at the solution, f_0, and moves successive iterations in the direction of increasing posterior probability. The algorithm stops when $\|g - s(h * f)\|^2 \leq \|n\|^2$, that is, when the variance of the residual image is less than or equal to the variance of the noise. This is the condition that would be satisfied if the true solution were known. An interesting property of this algorithm is that, in practice, it rarely produces a solution whose residual variance is much below the noise variance. This property allows us to make a rough check of our noise estimate.

The nonlinear film response is very important and prevents a quick linear-solution method from producing accurate results. Photographic film is not only a nonlinear recording device, it also possesses singularities caused by saturation and fog. If the film is used under optimal conditions, these singularities can be avoided by proper exposure. Unfortunately, most photography is not done under optimal conditions.

A major problem with the Zapruder film was with saturation effects. The sun reflecting from the chrome of the automobiles produced brightnesses that were beyond the recording capabilities of the film. A saturated area contains no useful information for the restoration method. The restoration scheme must be modified to not attempt restoration in this area. Further the scheme must make minimal use of information in this area for the restoration of other points. The space domain processing of the nonlinear MAP method is particularly adaptable to these modifications.

A binary saturation map was generated by flagging all points at or above the saturation level of the film. The effect on restoration of the saturated areas is not limited to the immediate area but extends to points around it. An estimate of the extent of this affected area was obtained by blurring the binary saturation map with the system point spread function. A threshold was determined empirically and a new binary map was obtained by flagging all points in the blurred map above the given threshold.

This saturation map was used as a guide for which points to restore. If a point was flagged, that point would remain unchanged by the restoration algorithm. The flagged points would, however, have some effect on neighboring points, but this effect was minimized by the local nature of the area and the extended range of the map generated by blurring the original saturated areas. The MAP algorithm without the saturation map produced a ringing around the saturated areas which increased in size and severity with each iteration. Eventually this ringing destroyed information in a large area of the picture. The modified algorithm eliminated this effect and produced the images shown later in this paper.

The information required to generate a model for the nonlinear function s was obtained from standard Kodak published film response (D log E) curves. The curves were sufficiently linear through most of their domain to permit linear approximation except in the area of the toe and shoulder (fog and saturation points).

A separate restoration was made for each color-separated scan. Each color was restored with its own nonlinear response function and its estimated noise.

Typical Restoration Activities

We know from extensive prior experience with image restoration that there is a severity of blur beyond which any restoration attempt is hopeless. Further, the better the initial image, the more we could potentially learn by restoring it. Each frame throughout the time sequence of interest, was visually categorized into one of five subjective groups: good, fair, blurred, badly blurred, and hopeless. Unless the frame was of unusual interest to the Select Committee we only attempted to restore images from the best two categories.

The important portion of each of 16 frames was restored using the blur deduced from the cepstral analysis. We arbitrarily treated those images which were only slightly blurred as if they had one picture element radius of out-of-focus blur. This treatment results in a qualitatively "crisper" image.

From a practical standpoint, the MAP algorithm always converged in 10 to 12 iterations. That is, the residual image described above became less than the estimated noise variance in 10 to 12 iterations on the image.

Figures 3 and 4 show original and restored versions of Zapruder Frames 193 and 312, respectively. Both of these were originally categorized as "good" and show the results of the "crispening" described above.

In all image restoration activity, the limit on the restored quality is determined by the image noise. If the noise is random, we should be able to reduce its effect by averaging several images of nearly identical scenes. The variation in scene from frame to frame of the Zapruder film made such an averaging infeasible. However, the "grassy knoll" area of the Nix film is sufficiently invariant over eight frames that we could average those frames. Then, in principle, the signal-to-noise ratio would improve by a factor of $\sqrt{8}$. Twelve identifiable control points were found on each of the eight frames. With these control points, the eight frames were registered and averaged. Figure 5 is a split screen image showing a single original frame and the MAP restored version of the average image. The expected reduction in image noise was observed in the averaged frame. Note that the restoration is essentially free of the "clumpiness" seen in Figs. 3 and 4, which are typical of restored images.

INTERPRETATION OF RESTORED IMAGES

Image restoration usually becomes a trade-off between increased sharpness and control of the image noise. The experienced analyst will usually use both the original and the restored image for interpretation. The present work was no exception. A number of the original/restored Zapruder pairs showed the positions of the President's head more clearly for mensuration than on the original alone. On one frame it was possible to resolve the image of the President's nose more clearly from the image of Mrs. Kennedy's jacket, thus making subsequent analyses more reliable.

Greater interpretive gains were possible on the Nix film because of the reduced noise that resulted from frame-averaging. It became apparent that the ill-defined shapes, which are claimed by some persons to be a "face-on" view of a rifleman in firing position, are nothing but a pattern of sun and shade on the wall of the pergola at the top of the "grassy knoll."

PHOTOGRAMMETRY, FRAME 413

A number of Zapruder frames, centered roughly on Frame 413, show what is thought to be the head of a person looking at the presidential limousine. Some persons claim that this head belongs to a person who is holding a rifle and using the bushes for concealment. We selected Frame 413, which shows this head the most clearly, for analysis of this claim (see Fig. 6). Two types of analysis show nothing suspicious about this person. One analysis attempts to identify the color of the object, alleged by some to be a rifle, which the person may be holding. The other makes an estimate of the person's position, based on elementary photogrammetry.

The color analysis relies on the ratio of exposures of the three emulsions of the Zapruder film. The procedure is precisely analogous to that used for analyzing the images obtained from earth resource satellites. The satellite photographs consist of images in several wavelength bands of illumination. It is assumed that distinctly colored regions on the earth's surface will have characteristic signatures in these multispectral photographs. However, differences in angle between the normal to the earth's surface and the image plane obscure these signatures. It has been found that by studying the ratios of the intensities in all pairs of wavelength bands, these surface-angle effects are removed. If the "man in the bushes" were holding a rifle, the sun angle might make it difficult to distinguish the weapon from the bush limbs about it. We studied the ratio images that we obtained from the transmittance of the film i the three emulsions. There were no features near the head that were different from the general surroundings; that is, no rifle was found.

The geometrical analysis consisted of laying lines of sight on a map of Dealey Plaza. These lines run from Zapruder's known location to the two light poles that are visible in Frame 413. These lines are indicated on the map in Fig. 7. This layout shows that the line of sight passing through the head is 2° to the right of the line passing through the light on the north side of Main Street. This line of sight passes across the landing on the stairs down the knoll to Elm Street at a position where R. E. Sprague[7] places three spectators. A further clarification of Zapruder Frame 413 can be obtained from Nix's photograph, Fig. 5. In this photograph we see Zapruder on the right. When his camera pointed toward the landing, he was looking down through the tall bush in the corner formed by the wall on which he is standing. This would mean that the bush is between Zapruder and the person of Frame 413. If that person is indeed standing on the landing, he is approximately 27 feet from Zapruder. Assuming a head width of 0.67 feet, the angle subtended is 1.4°. The head in Frame 413 subtends an angle of 1.35°. Thus, the head size is consistent with that of an individual where Sprague places "Hudson and two friends."

It is most likely that the "man in the bushes" seen in Zapruder Frame 413 is an individual standing on the steps in the open. That person is being photographed through a bush located quite near Zapruder.

SUMMARY

This portion of this paper is unusually short, for the objective at LASL was to produce improved imagery and analysis tools for the benefit of other persons on the Photographic Evidence Panel. We developed successful techniques for restoring locally intensity-saturated images. These images did clarify details from the original, which made subsequent analyses and conclusions more certain. In addition to image restoration, plus limited interpretation from those images, we also did a quantitative color analysis and a detailed mensuration on one frame that is alleged by some to show a gunman late in the Zapruder film. In no case did the images worked on at LASL directly reveal multiple gunmen. On the contrary, they deny the presence of two of the alleged gunmen.

ACKNOWLEDGMENTS

The LASL work for the Photographic Evidence Panel was a group effort. The authors collectively acknowledge

substantial and important contributions from C. W. Cox, R. O'Connor, and R. C. Bagley. In addition, we relied heavily on analytic techniques and software developed by numerous other persons in the LASL Digital Image and Signal Analysis Group.

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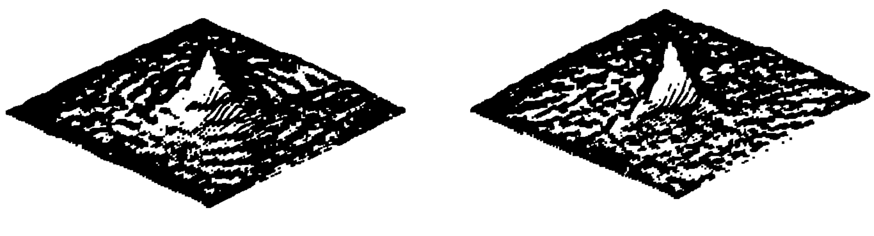
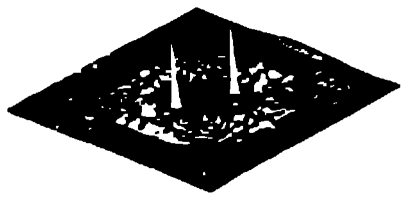


Fig. 1a. Power spectrum showing well-defined zeros due to out-of-focus blur.

Fig. 1b. Typical power spectrum, in which zeros are obscured by noise.



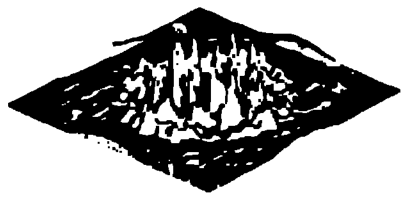


Fig. 2a. Cepstrum of motion-blurred image.

Fig. 2b. Cepstrum of out-of-focus image.

Fig. 2c. Top view of perspective plot of Fig. 2b.

Fig. 3. Upper image is original of Zapruder Frame 195; lower image is restored version of same frame. (A severe Moire pattern arose on this image during half-toning. The Moire is interference between the raster lines on an image-display and the lines on the half-tone screen.)

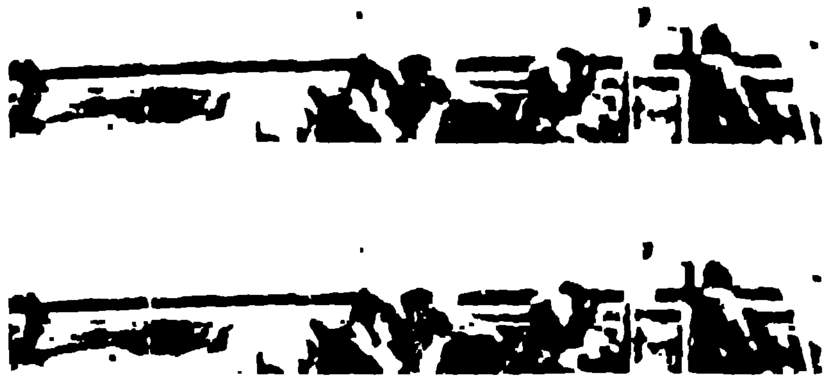


Fig. 4. Upper image is original of [illegible] frame [illegible]; lower image is restored version of same frame.

Fig. 5. Upper image is original of Nix frame [illegible]; lower image is restored version of an average of eight frames. (Detail of highlight was lost during half toning for publication.)

Fig. 6. Zapruder Frame 413 showing light posts used for photogrammetry and head (immediately to right of center, bottom edge of frame).

Fig. 7. Sketch map of features in Dealey Plaza relevant to photogrammetry of Frame 413, Fig. 6.