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Imaging techniques utilizing optical fibers and tomography

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Abstract

Two-dimensional, time-dependent images generated by neutrons, gamma rays, and x-rays incident on fast scintillators are relayed to streak and video cameras over optical fibers.

Three dimensions, two spatial and one temporal, have been reduced to two, one in space and time utilizing sampling methods permitting reconstruction of a time-dependent, two-dimensional image subsequent to data recording. The manner in which the sampling is done optimized the ability to reconstruct the image via a maximization of entropy algorithm. This method uses four linear fiber optic arrays typically 30 meters long and up to 35 elements each. A further refinement of this technique collapses the linear array information into four single fibers by wavelength multiplexing. This permits economical transmission of the data over kilometer distances to the recording equipment.

Introduction

It is often the case that trade offs can be made between time resolution, spatial resolution, system cost, and system reliability in imaging experiments. As an example, we often require reduced spatial information while time resolution and sampling frequency are of utmost importance. Another case may be a trade off of spatial resolution for an increase in system reliability. This is done by relaying a time-integrated image over long distances of optical fiber to active components such as cameras in a recording trailer. Remote recording of the image also has some cost savings if the most expensive components of the experiment are recoverable after the test.

In this report we describe two techniques we are investigating for imaging experiments that fall into the two categories of the examples above. Both techniques make use of a fiber optic tomography system to reduce the two-dimensional spatial information to one dimension. In the case of the first example, the one dimensional image is swept on a streak camera and a time resolved set of profiles with time resolution and sampling frequency not possible with conventional gating cameras is produced. An experiment of this type was developed and carried out at the Nevada Test Site. (1) One set of profiles or an average of several are used to tomographically reconstruct the 2D image at the time of the profiles. In the case of the second example, we use wavelength multiplexing to further reduce the one-dimensional image to a few optical fibers for transmission over long lengths of optical cable for reconstruction at the other end.

This report describes laboratory systems for the two examples given above; the streak tomographic system and the wavelength multiplexed tomographic system. We will give results of preliminary measurements of system efficiencies and examples of reconstructions of images taken through the systems pointing out current problems we have encountered and our future path of investigation.

Fiber optic tomographic imaging system

The 2D image is tomographically reduced to a "view" by integrating through the image along a line to form an "element" of the view. A number of consecutive parallel integrations through the image produce an integrated profile or "projection integral" of the image corresponding to the view. That is for a 2D image given by $I(x,y)$,

$$G_i(t) = \int I(x,y)dt \quad \text{Eq. 1}$$

in the projection integral along the t axis of an x,y,t coordinate system at an angle θ to the x,y coordinate system and in one of L elements of M views of the image taken at different θ .

Equation 1 can be achieved optically by the system shown in Fig. 1 (Ref. 2). The figure is most easily understood by considering that light which enters the fiber from the image is equivalent to back lighting the fiber and projecting the fiber onto the image. As shown, each fiber produces a strip along the image where the projection integral of Eq. 1 is taken. Unfortunately, the integral is weighted along the direction of integration because of the roll-off in the numerical aperture of the fiber and because of a factor proportional to the length of the dashed cords in the circle projected by the fiber acceptance cone onto the lens. This unwanted weighting is minimized by oversampling the image in the direction of integration by moving the cylindrical lens farther from the image at the cost of optical efficiency. It can also be mathematically corrected to some extent during reconstruction as described below. The view is then formed by imaging the target through the cylindrical lens onto a coherent fiber optic linear array.

Fig. 1. Simple tomographic imaging system using a single cylindrical lens and linear fiber optic array.

We have used variations of this system for various applications where different optical constraints made it necessary to modify the design (Ref. 3). Two systems are described in more detail in this report.

Tomographic reconstruction

Once a one-dimensional representation of the image is obtained, it is reconstructed using the MENT algorithm of Minerbo (Ref. 4). The projection data is given by $P_i(s)$ and ideally, $P_i(s) = G_i$. MENT defines an image entropy given by

$$H = - \iint dx dy f(x,y) \ln [f(x,y)A] \quad \text{Eq. 2}$$

where A is an arbitrary amplitude factor for f . The projections are taken as constraints and a Lagrangian is formed as

$$\mathcal{L} = \iint dx dy f(x,y) \ln [f(x,y)A] + \sum_{i=1}^{LM} \lambda_i(s) [P_i(s) - G_i(t)] \quad \text{Eq. 3}$$

where the $\lambda_i(s)$ are the usual Lagrange multipliers. To maximize the image entropy, the variation of Eq. 3 is taken with respect to the variation of f to find the extremum resulting in an expression for f given by

$$f(x,y) = \frac{1}{A} \sum_{i=1}^{LM} h_i[s_i(x,y)] \quad \text{Eq. 4}$$

where $h_i(s)$ is an unknown function of the Lagrange multipliers and $s_i(x,y) = x \cos \theta_i + y \sin \theta_i$. The $h_i(s)$ are found from the constraint equations

$$P_i(s) = h_i(s) / \iint_{k \neq i} h_k[s_k(x,y)] \quad \text{Eq. 5}$$

The system of equations defined by Eq. 5 can be solved numerically using a Gauss-Seidel method. If weighting in the t direction is present, the solution of the equivalent to Eq. 5 becomes prohibitively time consuming. If the weighting in the t direction is Gaussian however, the constraint equations again take a form similar to Eq. 5 and solution for the $h_i(s)$ is again tractable (Ref. 5).

C.T. Motternhead currently of Los Alamos National Laboratory has made a number of improvements to the original algorithm so that it more easily handles real data (Ref. 6). Motternhead and Johnson (Ref. 7) have added the ability of using a time integrated 2D image as a further set of constraints for reconstruction of time resolved streak tomographic images.

Streak tomography system

The use of a streak camera and tomographic imaging system to produce "high-speed movies" has been suggested by C. T. Mottershead (Ref. 7). To test the system in the lab, we have chosen as an object of study, laser generated shock waves in low pressure air (Ref. 9). These produce a brightness on a time frame within an order of magnitude of experiments we expect to do on underground tests. The imaging system we expect to use for these studies is shown in Fig. 2. The lens system was constrained to be outside the laser target chamber with a 10.0 cm observation window. Each of the four views consists of 27, 4.0 m long 200 μ m o. d. by 160 μ m diameter core, step index quartz fibers with a numerical aperture of about 0.2. The number of elements versus views was chosen after modeling a perfect optics system in which we assumed between 100 and 150 resolvable elements. We also assumed at least one axis of near symmetry. The individual linear arrays form one array at the streak camera and are separated by blank fibers and calibration fibers. The arrays are built by EG&G Santa Barbara and EG&G Las Vegas fiber optics group using techniques developed at these locations.

Fig. 2. Laboratory streak tomography system for observation of laser generated shock waves.

The efficiency of the optics system was measured as follows: A Lambertian strobe source with a 400 nm filter was used to back light a 1cm square placed at the target position. The strobe was pulsed 10 times and the output was measured at the lens position and at the output of the streak end of the array using a calibrated integrating radiometer. The results were normalized to a single strobe pulse and a single fiber which sampled the square image parallel to the side of the square. We measured 4.0×10^{-9} J/cm² at the position of the objective lenses and 6.5×10^{-12} J/fiber at output of the array. About 14 fibers spanned the 1cm square so each fiber sampled .071 cm² of the Lambertian source. The sampled area of the source would have produced $.071(4.0 \times 10^{-9} \text{ J/cm}^2) = 2.9 \times 10^{-10}$ J/cm²/sample at the lens. We will define the ratio of these numbers as the coupling factor, that is the coupling factor = $6.5 \times 10^{-12} \text{ J/fiber} / 2.9 \times 10^{-10} \text{ J/cm}^2/\text{sample} = .023$. In way of comparison we note that for a fiber of this type in a spherical lens system, the highest the coupling factor could be is .035. A value of .023 probably is optimal because we have assumed that the fiber cladding is negligible in saying the square was totally sampled by 14 fibers. The .023 value only holds of course for Lambertian sources near the center of the field of view. The rolloff of the optical system illustrated in Figs. 3c and 3d would reduce this value near the edge of the field of view.

The streak camera system was designed by Paul Black now at EG&G Kirtland around an RCA C7345AJM1 streak tube. The camera uses a novel double ended PET ramp circuit designed by John Rohrer of EG&G Los Alamos and can be used in the range of 20 nsec to 5 msec total sweep time. The ramp becomes very linear within 10 nsec of triggering at all ramp speeds. We used a 40 mm microchannel plate image intensifier (MCP), a 40 mm to 16 mm fiber optic reducer and a Fairchild 1064 CCD camera. We have also used combinations of MCP, reducer and vidicon and reducer and silicon-intensified-target vidicon for readout. The CCD was operated in the non-interlace mode and oriented so that time was in the horizontal direction. Therefore, the camera had 244 samples in the spatial direction and 180 in the time direction. We measured a sensitivity of 3.5×10^{-8} w/fiber at 400 nm for a signal to noise ratio of one for the 100 msec sweeps used to take data in this report. The spatial resolution was about 200 μ m at the photocathode and the time resolution of the system is about 1/20 of the sweep window. Video data was recorded using an 8-bit digitizer synced to the CCD clock.

Figure 1a and b were obtained by backlighting the streak end of the array with a white light source and projecting the image onto a piece of drafting mylar. The photo was taken with a CCD camera and the digitizer and shows the sampling of the target by all the arrays in Fig. 1a and only the horizontally aligned array in Fig. 1b. In order to measure the

Fig. 3a. Target sampling pattern of all views of tomographic imager in Fig. 2.

Fig. 3b. Target sampling pattern of vertical view only.

rolloff in sensitivity of the system, we placed a horizontal 0.5 cm slit across a Lambertian d.c. light source and scanned the streak end of the array with a CCD camera. The results for the horizontal array are given in Fig. 3c. Rolloff in this direction can be trivially corrected by dividing the data by the curve in Fig. 3b. The rolloff in the vertical direction was measured by translating a horizontal 0.05 cm slit across the light source which was long enough to illuminate the six central fibers of the horizontal array. The output at the streak end of the array was measured with a radiometer versus position of the slit. The results are shown in Fig. 3d along with a best fit Gaussian curve to show that it is possible to correct for the non-uniform weighting of the projection integral. It can be seen that because of the constraints on the optics system induced by the laser target chamber, that there is considerable rolloff in sensitivity in both directions. Uncorrected, we expect the rolloff in sampling to enhance the center of the reconstructed image. We note that at this time we have not tried to improve the reconstructions by including the measured rolloff in the unfold process.

Fig. 3c. Fiber sampling sensitivity for the vertical view across a uniform target.

Fig. 3d. Gaussian best fit to rolloff in sensitivity along the direction of integration.

We have not yet imaged a laser generated shock wave but have obtained static data by backlighting a number of targets with a uniform Lambertian strobe light source synced to the streak. The first target was a 1.0 cm square. Ten lines of the streak readout camera were averaged to provide the profiles. A contour plot of the results of the reconstruction are shown in Fig. 4a. We next illuminated a set of five 3mm spots centered on the corners and center of a 1cm square. The results of the five-hole pattern reconstruction are shown in Fig. 4b. The results of the five hole pattern are good when one considers that only 4 to 5 fibers per view sampled each spot and that for some views, up to 3 spots were in line along a projection integral.

Fig. 4a. Contour plot of tomographically reconstructed square from profiles taken with the system of Fig. 2.

Fig. 4b. Contour plot of tomographically reconstructed five hole pattern from profiles taken with the system of Fig. 2.

We next illuminated a photograph of a laser shock wave taken with an Imacon framing camera and printed as a transparency. The photo was scanned with a densitometer to produce the digital photo in Fig. 5a. The results of the reconstruction are shown in Fig. 5b. This image bears some resemblance to those we expect to record on underground experiments in that it exhibits a preferred axis of symmetry which was aligned with one view. As can be seen from Fig. 5b, if only low quality spatial resolution is required in exchange for many time samples, the reconstruction is not unreasonable.

Wavelength multiplexed tomographic system

Once the image has been tomographically directed it is possible to use a dispersing system to transfer light of slightly different wavelength from each array fiber onto a single fiber for transmission. At the receiving end, an equivalent dispersing system can be used to decode the light and reproduce the tomographic view for recording. In principle it should be possible to obtain time resolved images using wavelength multiplexing, however the large amount of light required and problems with chromatic dispersion in the fiber make time resolved wavelength multiplexed tomography not feasible for nuclear underground test experiments and we have only concentrated on time integrated wavelength multiplexed tomography.

The method we use for multiplexing the imaging array has been previously studied (Ref. 10) for other applications. Figure 6 is a schematic of the optical system used for our laboratory experiments. The only constraints on the tomographic imager are that the field of view be 6.0 cm and the optics be no closer than 30 cm to the target. Therefore, we were able to design an imager that sampled the target very uniformly using a compound cylindrical lens. The rolloff for this imager is less than 5% in any direction across the field of view. We again used the 200 μ m by 163 μ m quartz fiber for the 27 fiber linear array. The compound cylindrical lens consists of three separate closely spaced simple cylindrical lenses; a 19 mm focal length and a 25.4 mm focal length cylindrical lens with symmetry axis at right angles to the linear array separated by a 8mm focal lens with its axis perpendicular to the other two lens axis which serves as a field flattener. The previously defined coupling factor for this imager was measured and found to be .022.

Fig. 5a. Digital image of a laser generated shock wave produced from a densitometer scan of a transparency image used as a tomographic target for Fig. 5b.

Fig. 5b. Reconstruction of 5a after the transparency had been tomographically imaged through the system of Fig. 2.

Fig. 6. Laboratory wavelength multiplex tomographic system.

The multiplexer for this laboratory system consists of a direct view prism and the two lenses, L1 and L2. Because of the prism, only a small band of wavelength can couple from each fiber in the linear array to the single short distance fiber. The single fiber transmits the multiplexed light to the demultiplexer which would presumably be located uphole away from the nuclear blast. The demultiplexer behaves like the multiplexer in reverse, producing an image of the linear array on the readout camera dispersed according to color. The readout camera we used consisted of a MCP coupled to either a linear reticon or a 2D CCD camera. To avoid complexity, we only set up a single view system. We then take four sets of data by rotating the target 45 degrees each time to produce the equivalent of four tomographic views. The targets are again backlit by a Lambertian strobe source.

A measure of the efficiency of the multiplex system was taken by illuminating a single fiber in the linear array with a 3nm FWHM filtered d.c. light centered at 630 nm. A 3nm FWHM was less than the FWHM coupled from each array fiber to the single transmission fiber. The single transmission fiber was positioned to optimally couple to the output of L2. The ratio of the output of L4 to the output of the linear array was measured with a radiometer to be .048. Assuming the lenses and the prisms are only 80% transmissive and the ratio of the quartz to short distance fiber areas is .38, we calculate an efficiency of .156.

The combination of the backlighting strobe emission spectrum, the MCP photocathode sensitivity, chromatic aberrations in the optics system and non-linear dispersion of the prisms produces a non-uniform sampling of the target along the direction of the linear array. To determine what this correction should be, we used a 1cm slit which extended across the field of view parallel to the linear array. An image of the focal plane of the demultiplexer is shown in Fig. 7. The wavelength scale was determined by placing interference filters of different wavelengths at the output of the linear array.

Fig. 7. Correction applied to each view for reconstruction rolloff is due to non-uniform sensitivity of the system in Fig. 6 versus wavelength.

We next backlighted a 3.2 cm square centered in the field of view with the Lambertian strobe source. Figure 8a is one view of the square with the direction of integration parallel to the sides of the square. One would expect the profile to be a square wave. Figure 8b is the same profile after applying the wavelength correction of Fig. 7. It can be seen that there is very little improvement and that the sides of the square wave have considerable slope. The reason is that the spatial resolution through the multiplexer system from the output of the linear array to the input of the camera is poor; on the order of several fiber diameters. We have since determined the cause of this effect to be chromatic aberrations at the input to the camera and at input to the transmission fiber resulting in a finite difference in the focal point for each color. The result is that the different wavelengths from several array fibers are mixed at the input to the single transmission fiber and there is a blurring of the demultiplexed image at the camera. Both effects lead to image degradation.

Fig. 8a. Broadside view of square before wavelength correction.

Fig. 8b. Broadside view of square after wavelength correction of Fig. 7 has been applied.

Despite these problems the square as well as a similar five-hole pattern were reconstructed from the data and the results are shown in Fig. 9a and 9b. As one would expect, the square shows rounding of the edges and corners due to the poor spatial resolution of the profiles.

The prisms were initially chosen for efficiency but lack enough dispersion for multiplexing narrow fluor emissions of 50 nm for underground test applications. As discussed above, the lens/prism system was later found to have large chromatic aberrations which degraded resolution through the system. Both these problems can be overcome by using reflection gratings at the expense of some optical efficiency. The gratings would also be much less expensive than the prisms. We are currently putting together such a system to operate in the 635 nm to 665 nm region for transmission of images generated by nuclear irradiation of special red scintillators for transmission over kilometer lengths of Corning

short distance 140 μm /100 μm fiber.

Fig. 9a. Contour plot of tomographic reconstruction of square imaged through the system of Fig. 6 after applying the wavelength correction of Fig. 7.

Fig. 9b. Contour plot of tomographic reconstruction of five-hole pattern imaged through the system of Fig. 6 after applying the wavelength correction of Fig. 7.

Conclusion

Initial demonstration of both tomographic imaging techniques described in this report indicates that the techniques look promising. It is also clear that effort must be put into the optical system design to obtain best results. The effort is particularly needed for the wavelength multiplexing scheme where both the multiplexer and imager can introduce image degradation. The results in this report also demonstrate that even imperfect optical systems still yield profiles that give reasonable reconstructions of the original image. So far there seem to be no insurmountable problems associated with these techniques and we hope to optimize both techniques for our applications in underground nuclear test imaging within the next year.

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